



GREENBOOK
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THE IMPACT OF CLIMATE CHANGE ON FLOODING

WORKSTREAM 4: RESEARCH REPORT

2019



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Funded by



IDRC | CRDI

International Development Research Centre
Centre de recherches pour le développement international

Canada



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Date	2019
ToDB reference	CSIR/NRE/ECOS/ER/2019/0001/C
Suggested citation	Le Maitre, D & Kotzee, I. 2019. <i>Green Book – The impact of climate change on flooding</i> . Technical report, Pretoria: CSIR

Disclaimer and acknowledgement: This work was carried out with the aid of a grant from the CSIR Long-term Thematic Programme, Pretoria, South Africa and the International Development Research Centre, Ottawa, Canada. The views expressed herein do not necessarily represent those of the IDRC or its Board of Governors.



TABLE OF CONTENTS

1	INTRODUCTION	6
2	BACKGROUND	7
2.1	Flood hazard	7
2.1.1	Regionalising observed data.....	7
2.1.2	Design flood estimation.....	8
2.1.3	Assessing catchment responsiveness.....	9
2.1.4	Simulating floods.....	11
2.1.5	Summary	11
2.2	Flood vulnerability.....	13
2.2.1	Physical exposure.....	13
2.2.2	Assets exposed	14
2.2.3	Participatory approaches	15
2.2.4	Summary	15
3	METHODOLOGY	16
3.1	Current climate and hydrological characteristics	16
3.2	Future climates and flood hazard.....	16
3.3	Flood hazard	17
3.4	Flood exposure.....	21
4	RESULTS.....	21



4.1	Climate and hydrological characteristics	21
4.2	Projected increases in extreme daily rainfall	25
4.3	Flood Hazard Index	27
4.4	Cederberg and Dihlabeng Local Municipalities	30
5	CONCLUSION	39
6	REFERENCES	41

TABLE OF FIGURES

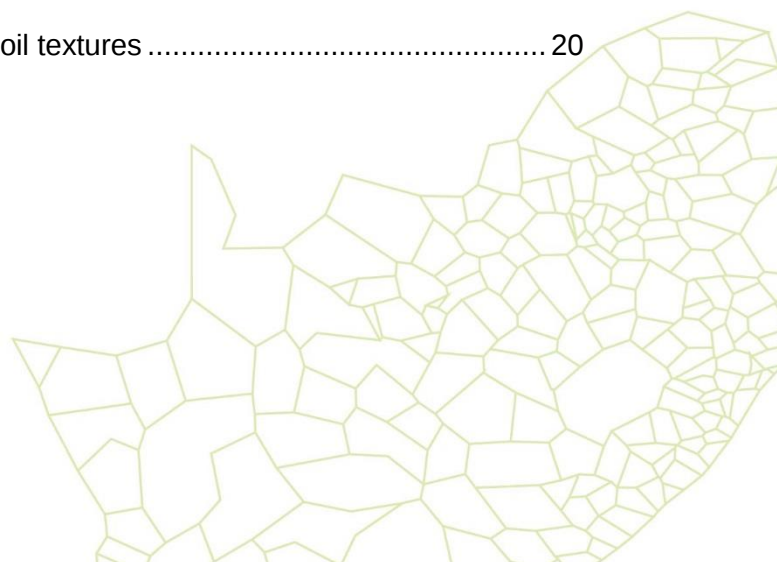
Figure 1: Diagram summarising the steps and inputs in the calculation of the flood hazard.	19
Figure 2: 50-year return period design on day (daily) rainfall for South Africa (Schulze et al., 2008). The class intervals are based on a geometric scale to reduce the influence of extreme values	22
Figure 3: The modelled highest daily stormflow in a 10 year period (Schulze et al., 2008). The class intervals are based on a geometric scale to reduce the influence of extreme values..	23
Figure 4: The variability in the stormflow between years (inter-annual) as a percentage of the mean stormflow (i.e. the Coefficient of Variation as a percentage) (Schulze et al., 2008)....	24
Figure 5: The regionalised K-ratio i.e. the ratio of the flood peak in m ³ /sec to the average annual flow in m ³ /sec for catchments in South Africa, Lesotho and Swaziland (Kovács, 1988). Digital version supplied by the Aurecon Group (Andre Görgens personal comm)	25
Figure 6: The mean ratio of the near-future (2021-2050) and current (1971-2000) extreme daily rainfall (95th percentiles) for each quinary catchment. Values greater than 1.0 indicate an increase in the extreme daily rainfall.	26
Figure 7: The mean ratio of the near-future (2070-2099) and current (1971-2000) extreme daily rainfall (95th percentiles) for each quinary catchment. Values greater than 1.0 indicate an increase in the extreme daily rainfall.	27
Figure 8: The Flood Hazard Index calculated by the SCIMAP model for the primary catchment area U showing the mean values per quinary catchment. Class intervals based on the standard deviation of the mean values per quinary catchment.	28
Figure 9: The mean flood hazard calculated by the SCIMAP model for the primary catchment area X (Inkomati River System) for each quinary. Class intervals based on the standard deviation of the mean values per quinary catchment.....	29



Figure 10: Mean Flood Hazard Index (FHI) per quinary (5th order) catchment based on the SCIMAP model run at the secondary catchment level. Class intervals based on the standard deviation of the mean FHI for the quinary catchments.....	30
Figure 11: The Cederberg Municipality showing the settlements and the flood hazard modelled for each one based on the SCIMAP model.	31
Figure 12: The proportions of the different settlements that are exposed (i.e. situated within 10 m of the estimated river level).	32
Figure 13: The land cover in the areas situated less than 10 m above the level of the rivers next to or passing through the settlements. Classes in the 2013/14 land cover (GTI, 2015) were combined into the main ones from the risk perspective	33
Figure 14: Cederberg Municipality showing the 1-day design rainfall (50 year return period) for each of the quaternary catchments. Data from Schulze et al. (2008).	34
Figure 15: The Cederberg Municipality showing the mean FHI estimated by the SCIMAP model for the quinary catchments in this area.	35
Figure 16: Dihlabeng Municipality showing the settlements and the flood hazard modelled for each one based on the SCIMAP model.....	36
Figure 17: The proportions of the different settlements that are exposed (i.e. situated within 10 m of the estimated river level).	37
Figure 18: The land cover in the areas situated less than 10 m above the level of the rivers next to or passing through the settlements. Classes in the 2013/14 land cover (GTI, 2015) were combined into the main ones from the risk perspective.	37
Figure 19: Dihlabeng Municipality showing the 1-day design rainfall (50 year return period) for each of the quaternary catchments. Data from Schulze et al. (2008).	38
Figure 20: The Dihlabeng Municipality showing the mean FHI estimated by the SCIMAP model for the quinary catchments in this area. Note that the class intervals differ a little from those in the national level map	39

LIST OF TABLES

Table 1: Hydrologic soil groups identified from soil textures	20
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1 INTRODUCTION

Like many other countries, South Africa has a history of floods ranging from minor, local events through to national disasters with widespread flooding generated by extreme events such as cut-off lows and cyclones, the most recent one being cyclone Dineo in February 2017 (Davis-Reddy and Vincent, 2017; Holloway et al., 2010; Kovács, 1988; Lund, 1984; Pharoah et al., 2016; Pyle and Jacobs, 2016; Roberts and Alexander, 1982; Sakulski, 2007; van Niekerk et al., 2016). Some information on the location of floods in southern Africa is available from the South African Weather Service ¹, the Dartmouth Flood Observatory (<http://floodobservatory.colorado.edu/>), datasets on global disaster hotspots (Dilley et al., 2005), and the Aqueduct Global Flood Analyser (see <http://floods.wri.org/#/country/209/South%20Africa>) (Ward et al., 2013; Winsemius et al., 2015) and other databases.

Flood risk, like many other risks, can be disaggregated into two main components (Balica et al., 2013):

- Flood hazard which focuses on the nature of the flood events and includes the likelihood and the severity of flood events
- Flood vulnerability which focuses on the effects of flood events on people, their livelihoods and infrastructure, and includes the degree of exposure, alternatively the magnitude of the consequences, and the resources available for them to recover from the flood.

¹ <http://sawweatherobserver.blogspot.co.za/search/label/flood%20damage>



2 BACKGROUND

2.1 Flood hazard

Along the coast flooding can be caused by high tides, storm surge and strong winds forming high energy waves and, thus, increased wave run-up. Inland floods are caused by large volumes of water which are generated by rainfall events. Both kinds of floods can occur together when the same storm drives coastal flooding and inland flooding and the two combine in estuarine environments. Inland floods are generated by rainfall in various ways including:

- very intense, short duration rainfall events which rapidly saturate (saturation excess) or exceed the ability of the soils to absorb the water (infiltration excess) (Beven, 2004; Manfreda et al., 2010) and result in short duration flash floods; or
- longer, less intense rainfall events, or a sequence of events which also saturate catchments and can result in long duration floods; or
- groundwater table rises in response to rainfall recharge (Musungu et al., 2012).

The focus of this document is on floods generated by surface water (fluvial or river-related floods) but the third cause is important in certain areas such as the Cape Flats near Cape Town. The methods for doing flood hazard assessments can be broadly divided into two categories – those based on analyses of observed or modelled floods and those based on observed or statistically predicted rainfall events (Smithers, 2012; Smithers and Schulze, 2003).

2.1.1 Regionalising observed data

Approaches have been developed using observed flood data which are then turned into regional estimates so they can be used in flood risk assessments (Benjamin, 2008; Smithers and Schulze, 2003; van Bladeren et al., 2007). Key weaknesses are that: (a) they do not give an estimate of the frequency of that flood (Van Bladeren et al., 2007); and (b) they are based on data from a particular catchment with specific properties and have to be generalised for regional use although this effect is reduced when data from sufficient catchments within a region are available (Kovács, 1988).



The regional maximum flood (RMF) approach used by Kovács (1988) applied an equation developed from an international study which linked upstream catchment area and observed maximum flood peaks (Francou and Rodier, 1969). The K-ratio derived from the equation represents the ratio of the maximum flood to the normal runoff. The upstream areas are divided into three ranges: areas $<1 \text{ km}^2$, the “storm zone” where the K-ratio is determined mainly by 15-minute rainfall intensity; a “flood zone” for areas $> 100\text{-}500 \text{ km}^2$ where the flood ratio is the catchment characteristics and the rainfall; and a “transition zone” between 1 and $100\text{-}500 \text{ km}^2$ where there is mixed response (Kovács, 1988). In South Africa the transition zone appeared to apply up to 200 km^2 and the reliability of the estimated K-ratio decreased as catchment area decreased. The K-ratios were generalised to regions using information on the catchment characteristics and 3-day rainfall to create a map for the country (Kovács, 1988). There have been a number of local refinements of this approach, some combined with models (Nortje, 2010; Pegram and Parak, 2004; Vischel et al., 2008), but only one has used sites from across the whole country (Görgens, 2007). There have been similar approaches which incorporated flood frequency but they have also only examined certain catchments (Smithers et al., 2015; Van Bladeren et al., 2007). A couple of studies have derived regionalised flood magnitude and frequency information for southern Africa but generally at a relatively coarse resolution (Haile, 2011; Kachroo et al., 2000; Mkhandi et al., 2000), so the Kovács (1988) estimates are still used.

2.1.2 Design flood estimation

One of the standard modelling approaches, design flood estimation, was developed primarily for assisting engineers in designing structures to cope with predicted volumes of flood water (Smithers, 2012; Smithers and Schulze, 2003). This generally uses a simplified representation of the catchment and its potential to generate floods based on a variety of approaches. It is used for detailed analyses of single events, typically in small catchments, and uses statistical analyses of the regionalised characteristics of the rainfall which provide design rainfall amounts as inputs (Knighton and Walter, 2016; Knoesen and Smithers, 2008; Smithers, 2012; Smithers and Schulze, 2004, 2003; Van Bladeren et al., 2007). The most common modelling approaches used for event based analysis in South Africa are the Rational, Unit Hydrograph and SCS methods (Smithers, 2012). A disadvantage of these approaches is that they focus mainly on the rainfall while largely ignoring catchment behaviour, a limitation which becomes more important as catchment heterogeneity increases. Software packages are available to do this type of modelling under local conditions (Gericke and Du Plessis, 2013; Smithers, 2012; Smithers and Schulze, 2003).



An alternative method of estimating the flood hazard involves generating time series of river flows using a simulation model (Smithers et al., 2013):

- Selecting, setting-up and calibrating a suitable hydrological model for the catchment area in which the settlement is located. The model should be able to run on a daily time step (preferably hourly), should be able to represent the catchment properties and behaviour adequately and needs to be able to simulate the runoff following rainfall events. Once it is set up, the outputs are compared with observed data from the catchment and the parameters in the model are adjusted until its simulated flows match the observed flows sufficiently accurately (typically within 10%), a process known as calibration. The model can be run using design rainfall data (Knighton and Walter, 2016; Knoesen and Smithers, 2008; Smithers and Schulze, 2004, 2003) or a range of historical high rainfall events to generate time series of runoff volumes. The ACRU model was tested in the Thukela River catchment and was found to perform reasonably well at simulating flood volumes (Smithers et al., 2013)
- These runoff volumes can then be used as inputs to a hydraulic flow-routing model which uses detailed information on topography and roughness of the river floodplain and adjacent areas to predict the depth (extent) and duration of the flood for vulnerable areas of the catchment (Zerger and Wealands, 2004). This model should preferably be calibrated as well.

Some flood models can combine these two steps. Following such an approach in this study is simply not feasible given the time required to source the necessary input datasets, calibrate the models, run them and interpret the outputs. These kinds of issues are the main reason why such an approach has not been applied across the country (Els and Van Niekerk, 2013). The number and location of the settlements is not known at this stage and there are few gauged catchments in the country, so it is likely that settlements will occur in catchments with no observed flow records, and obtaining suitable rainfall datasets could be problematic.

2.1.3 Assessing catchment responsiveness

An alternative approach is needed which is able to use information on the characteristics of the catchment to at least estimate its responsiveness to rainfall events whilst being applicable to a range of catchments. It needs to be able to represent how rainfall event size, duration and intensity interact with the characteristics of the catchment to influence its behaviour i.e. the volume and rate of flow of the runoff. Key factors in catchment responsiveness are the



topography, especially the steepness, the depth of the soils and the ability of the soils and subsurface systems to take-up (capture) and store the rainwater (Beven, 1987; Görgens, 2007; Jencso and McGlynn, 2011; Kourgialas and Karatzas, 2011; McDonnell, 2009; Merz and Blöschl, 2008a, 2008b; Sayama et al., 2011). Essentially this can be viewed as a combination of the extent and sensitivity of the runoff generating areas (Cheng et al., 2014) and the hydrological connectivity (the ease with which surface runoff moves across a landscape) (Hahn et al., 2014; Kourgialas and Karatzas, 2011; Lane et al., 2009, 2003). The RMF study took some catchment characteristics into account by including relief, catchment orientation in relation to the movement of storm-generating weather systems, general soil permeability, the main drainage network and any very large dams situated upstream (Kovács, 1988). The interpolation was based on mapped information on the different variables and expert judgement. Other studies have used the catchment area (which is always significant), mean annual precipitation, the river slope, mean annual rainfall and runoff, the longest stream length, grouped veld (vegetation) types and grouped K-regions (Görgens, 2007; HRU, 1972; Van Bladeren et al., 2007). One study found that including a range of catchment characteristics did not improve the performance of a regional flood frequency analysis (Smithers et al., 2015). The importance of considering the hazard is taken into account by the Flood Vulnerability Index which uses physical and environmental indicators for different sizes of study areas (river basin to urban area), including rainfall characteristics, land cover, topography, river flow characteristics and dam storage upstream (Balica and Wright, 2010).

Catchment responsiveness also varies depending on its initial state prior to a given rainfall event, particularly how “wet” it was prior to the rainfall event of interest (antecedent wetness) (Brocca et al., 2011; Longobardi et al., 2003). Typically, the wetter it is the more likely it is to produce a greater volume of runoff. The more responsive a catchment is, the more likely it is that antecedent wetness will have a marked impact on runoff, but even an unresponsive catchment will respond to rainfall when antecedent wetness is high. This level of assessment is best suited to detailed studies as it is not readily accommodated in a flood hazard assessment approach at the level of this study. This issue was addressed to an extent in the RMF analysis by including three-day rather than one day rainfall (Kovács, 1988).

Models of hydrological connectivity incorporate many of the factors that make catchments responsive to rainfall so an analysis of the hydrological connectivity can provide useful insights into flood generation potential. The data requirements are typically relatively modest - involving a suitable digital elevation model for calculation of slopes and connectivity, a river network and information on the soils. A quantification of the connectivity combined with data



on the design rainfall or extreme rainfall predicted for those catchments could give an acceptable indication of the flood hazard. Projections of future design or extreme rainfall can be used to give an indication of the potential for the hazard to increase in the future (Milly et al., 2002; Prudhomme et al., 2010; Steinschneider et al., 2015) while acknowledging the uncertainties in such projections (Johnson et al., 2016; Kundzewicz et al., 2013). As far as we know there have not been any studies which have used hydrological connectivity in flood hazard modelling in South Africa but the use of related catchment characteristics such as relief, stream density and stream slope in flood hazard modelling suggests that it could be useful.

2.1.4 Simulating floods

Many of the local studies have made use of information on the magnitudes of observed floods using either the data collated and published by Kovács (1988) or obtained from the Department of Water and Sanitation (Görgens 2007). Hydrological models can also be used to simulate streamflow records using historical rainfall and these records can be analysed for flood volumes and frequencies. Simulated flow records have been generated using the ACRU model at the quaternary (Schulze et al., 2008) and sub-quaternary scale. This spatial dataset includes design daily rainfall for 2 to 50 year return periods, mean annual runoff and stormflow, and the highest stormflows in 10 years. If they can be accessed, the 50 year records of daily flows could be analysed to provide flood recurrence (magnitude and frequency) relationships. One concern is that hydrological models are typically parameterised to produce “normal” flows and those settings may not be appropriate for simulating extreme floods. Distributed, raster and terrain-model based hydrological models such as TOPKAPI (Vischel et al., 2008) or Mike-SHE (Glenday, 2015) are also promising but do have intensive data requirements and need further evaluation.

2.1.5 Summary

There is no single approach or dataset that is recommended as the best for estimates of flood magnitudes and frequencies in South Africa. Detailed approaches based on generating flood lines and estimating flood durations are impractical given the limitations on the available data (Els and Van Niekerk, 2013) and the time and resources they would require. Most of the studies recognise the RMF method and dataset developed by Kovács (1988) as the baseline for assessing how well their method performs. The problem though is that the RMF does not provide an estimate of the frequency.



Another option would be to make use of Kovács (1988) K-ratio regions and estimate the missing flood frequencies. Pegram and Parak (2004) found that Kovács's (1988) statement that his estimates of flood magnitudes corresponded roughly to a frequency of 1 in 200 years was reasonably accurate for the K-ratio regions which cover most of South Africa. If we assume that is the case, then we can also estimate floods for different return intervals for each of Kovács's (1988) K-ratio regions using the approach for estimating flood magnitudes at other intervals (e.g. 1 in 50 years) suggested by Pegram and Parak (2004). One disadvantage is that this approach relies on what is now a very dated data set on historical floods and that the magnitudes for different frequencies are not estimated from the raw data but via a generalised relationship. A weakness of both methods of providing quantitative estimates of flood magnitudes and frequencies is that detailed hydraulic modelling would be needed to interpret what such a flood could mean in terms of depths and durations. As noted above, this is simply not feasible within the scope of this project although it would provide a relative measure of the hazard.

However, there is a third option which is to use selected climatic and environmental (e.g. catchment) characteristics to generate a relative flood hazard. We are proposing to follow two separate processes to characterising flood hazard.

The first is to characterise flood hazard based on the environmental characteristics of the catchment. We will use the SCIMAP software to analyse the hydrological responsiveness and connectivity of the catchment (Hahn et al., 2014; Lane et al., 2009). We will supplement this with two additional sources of information. The one is the Kovács (1988) K-ratio value for a region which indicates the ratio of the discharge flood peak to the normal discharge in that river system which is roughly equivalent to the 1:200 year flood peak. This can be provided for every settlement. The second is to extract the information on the design rainfall, high daily rainfall and stormflows from the hydro-climatic atlas datasets developed from observed data (daily rainfall) and modelled data (stormflows) (Schulze et al., 2008).

Climate models allow us to predict how changes in the composition of the atmosphere due to anthropogenic emissions will affect the characteristics of the rainfall. Climate models generally agree that rainfall intensities (e.g. daily rainfall amounts) will increase in future but also show that the spatial patterns in the amounts of those increases will vary depending on the emission scenarios and the particular global climate change model that is being used (Davis-Reddy and Vincent, 2017; Dearing et al., 2014; Dedekind et al., 2016; Engelbrecht et al., 2013, 2011;



IPCC, 2014; Zhang et al., 2013). Since intense rainfall is the main driver of floods, we have extracted the 95th percentile of the daily rainfall for the current climate, projected near future and far future climate generated as part of the Green Book project.

2.2 Flood vulnerability

There is a considerable body of literature on assessing flood vulnerability, namely the consequences of a flood for a given settlement or situation (Balica et al., 2013; Benjamin, 2008; Connor and Hiroki, 2005; Rufat et al., 2015; Turner et al., 2003). Although a wide range of terminology and variables are used, vulnerability can generally be described as the combination of exposure, susceptibility and resilience as used in various vulnerability indexes, including the well-established Flood Vulnerability Index (<http://unescoihevfi.free.fr/vulnerability.php>). Exposure refers to the characteristics of the flood, predisposition (tendency) of people and their assets to flooding, and the value of those assets. Susceptibility is about the community's ability to take appropriate actions both in mitigating or adapting to the flood and during the flood. Resilience is about the ability of the system, especially the socio-economic system, to recover after the flood and involves both social and governance systems. A very wide range of indicators can be used at the whole catchment, sub-catchment of a settlement itself, and the individual urban units to assess each of these aspects (<http://unescoihevfi.free.fr/indicators.php>) but many of these are redundant and simplifications have been recommended (Balica and Wright, 2010; Rufat et al., 2015).

2.2.1 Physical exposure

The first component of exposure is related to the flood hazard as it is directly linked to both the potential of the catchment to generate floods (whole basin) and the setting of the settlement and the likelihood of flood waters extending into or inundating (portions of) the settlement (e.g. proximity to a river, elevation above the river bed, river-bed slope and curvature). These factors are those that are typically taken into account in defining 50 and 100-year flood lines but, unfortunately, flood lines are only available for a few areas and not at a national level. However, information on the physical (e.g. topographic) setting of the settlement can be used to provide estimates of this aspect of the exposure. Although a 30-m digital elevation model is not considered suitable for use in hydraulic modelling it can still provide data on elevations relative to a water-course and thus on one aspect of exposure.



2.2.2 Assets exposed

The mesozone data and/or land-cover information can be used to estimate the values of the assets, the numbers of people potentially affected and their susceptibility and potential resilience. This can then be combined with other aspects of the settlement typology, or measures of governance capacity to refine the assessments of susceptibility and resilience as used in the Flood Vulnerability Index (Balica and Wright, 2010). Many South Africans live in informal settlements and these are often located in flood-prone parts of the landscape (Van Niekerk et al., 2016) so this aspect of vulnerability will require special consideration. The 2014 national land-cover information (GTI, 2015) includes urban classes which can be used to identify where these settlements are located.

Suitable social and economic indicators in the Flood Vulnerability Index (FVI) include characteristics of the population, heritage, development levels, capacity and ability of emergency services, access, warning systems, extent and kinds of land use, and capacity to recover (Balica and Wright, 2010). After the screening the following indicators were chosen for each component of the social and economic FVI for the river basin scale (as an example):

$$FVI_{social} = f \left[\frac{P_{FA} * C_M}{P_E * AP * W_S * E_R} \right]$$

Where P_{FA} = population in flood prone area; C_M = child mortality (n children < 1 year old dying per 1000 births); P_E = past experience (% of people who have been affected by floods in the past 10 years); AP = awareness and preparedness (rated from 1-10, 10 = high); W_S = warning system (1 if no system, 10 if there is a system); E_R = evacuation roads (% asphalted [hard surfaced] roads). Child mortality was strongly correlated with the unemployment as a percentage of the working population and could be used instead.

$$FVI_{economic} = f \left[\frac{HDI * Ineq}{AmInv * E_R} \right]$$

Where HDI = Human Development Index; $Ineq$ = Gini coefficient for inequality; $AmInv$ = amount of investment as a percentage of the GDP; E_R = evacuation roads (% asphalted [hard surfaced] roads). The FVI_{social} and $FVI_{economic}$ are summed to give the total for those components. The results of the screening are presented for the sub-catchment and urban scales (Balica and Wright, 2010) but have not been included here. They typically include a different subset of the original variables and a greater number of variables. The decision of



which of these scales applies to each settlement can be determined once the settlements have been identified and their location within their catchments has been evaluated.

2.2.3 Participatory approaches

It is important to note that what has been described thus far is a top-down approach. Studies in South Africa have made a strong case for the bottom-up (participatory, community-based) approach to the assessment of social and economic vulnerability and resilience (Benjamin, 2008; Mukheibir and Ziervogel, 2007; Van Riet and Van Niekerk, 2012; Viljoen et al., 2001; Viljoen and Booysen, 2006). These aspects will be addressed in Workstream 1 of the Green Book project. Ecosystem-based adaptation can be very effective in reducing environmental risks (Black and Turpie, 2016; Bourne et al., 2016; Coetzee et al., 2016; SANBI, 2015, 2014; Van Niekerk et al., 2016) and should also be an important component of the responses implemented by the users of the Green Book. A participatory approach is also recommended assessing the economic and social components of the Flood Vulnerability Index (<http://unescoihevvi.free.fr/vulnerability.php>).

2.2.4 Summary

We will follow a two-step process to characterise exposure: (a) to identify the exposed areas by delineating areas that are less than a certain elevation (provisionally 10 m) above the estimated level of a watercourse (i.e. a river); and (b) identifying infrastructure within this area and characterising the social and economic attributes using the 2013-14 land cover classes and other information available from the characterisation of the settlements from the Green Book project.

Ideally, the FVI should be assessed with inputs from the affected communities and the representatives of the relevant governance structures but the feasibility of stakeholder involvement needs to be evaluated against the resources available for this project. Nevertheless, we believe that this top-down approach could be used to characterise the social and economic vulnerability of settlements and to prioritise them for interventions. The next step would be for those local authorities and affected communities to follow a participatory approach to risk mitigation and adaptation.



3 METHODOLOGY

The occurrence of floods is determined by features of the current local and regional climate and the characteristics of the catchments upstream of settlements, while the exposure and the vulnerability to the floods are determined by the location of part or all of the settlement and by the social and economic characteristics of the settlement and the parts affected by the floods.

3.1 Current climate and hydrological characteristics

The regional and local climate is a primary driver of the flood hazard, particularly the intensity and duration of the rainfall. There have been various studies of the rainfall characteristics but the most useful are those that have estimated design rainfall, the rainfall that is used in designing stormwater systems amongst others (Smithers et al., 2001; Smithers and Schulze, 2004, 2003). This involves using daily rainfall from weather stations and statistically analysing it to extract the frequency distribution and then the extreme values from that frequency distribution. We have chosen to use to 100-year return period one-day design rainfall which has been summarised at the quaternary catchment level for South Africa (Schulze et al., 2008).

Hydrological modelling has been used to estimate stormflows (i.e. those typically occurring after high rainfall for South Africa at a quaternary catchment level in South Africa (Schulze et al., 2008)). This model uses climatic inputs together with terrain, and cover and land management to estimate the river flows after high rainfall events. The 1 in 50-year flows were not available, so we have used the highest stormflows over a 10 year period as an indication of the flow volumes that can be expected

3.2 Future climates and flood hazard

Since intense rainfall is the main driver of floods (Smithers and Schulze, 2004) and rainfall intensity is likely to increase (Davis-Reddy and Vincent, 2017; Kundzewicz et al., 2013), we needed to obtain some estimates of the extreme daily rainfall in the future as modelled by Workstream #2. Although Workstream #2 generated high spatial resolution ($\pm 8 \times 8$ km) datasets from the climate model, the projected 95th percentile daily rainfall is still much less



than the rainfall amounts observed at weather stations. This is mainly because the relatively coarse spatial scale modelled rainfall cannot accurately represent the detailed spatial patterns of rainfall intensity in typical rainstorms. One way of overcoming this underestimation of the actual rainfall extremes, is to compare the frequency distributions of the observed and modelled rainfall and develop functions that can rescale the modelled rainfall to better match the observed rainfall. However, implementing a rescaling like this for the whole country is beyond the scope of this study. The next best alternative was to calculate ratios of the climate model predicted 95th percentile daily rainfall for the near future to the present, and far future to present, for each modelled 8x8 km cell, as an estimate of how the extreme daily rainfall will change in future across South Africa and for each settlement. This approach assumes that these shifts in the modelled rainfall intensities will be similar to those in the actual rainfall in future which is a reasonable assumption given that the same modelling system is being used in each case.

The average values of these ratios were extracted for each of the quinary catchments using bilinear interpolation in ArcGIS. Where the ratio of the future to the current extreme rainfall is greater than one (1), this indicates that extreme rainfall events are likely to be more severe in the future than they are now. These calculations were done for both the near- or mid-future (2021-2050) and the far future (2070-2099).

3.3 Flood hazard

The SCIMAP model was used to model flood hazard based on the catchment characteristics. It requires the following inputs:

- 1) Topographic data of appropriate spatial resolution and vertical precision and we used a 30 m Digital Elevation Model (DEM) with a planimetric accuracy of 15.24 metres (Chief Directorate Surveys and Mapping, 1990).
- 2) Land-cover data for which we used the 2000 national land-cover data for South Africa, Lesotho and Swaziland derived from satellite images and field verification (Van den Berg et al., 2008). We used this one rather than the 2013-14 dataset because it was complemented by a database which gives some hydrological characteristics for each land cover class (Thomas, 2015).
- 3) Design rainfall data for a 50-year return period were taken from the South African Atlas of Climatology and Agrohydrology (Schulze and Smithers 2007). Design rainfall is a theoretical storm event based on rainfall intensities (using historical rainfall data)



associated with a frequency of occurrence and a set duration and represents typical rainfall amounts associated with 1 in 50-year floods (Smithers and Schulze, 2003).

- 4) Hydrologic soil type data was inferred from soil texture data obtained from the Soils and Terrain Digital Terrain Digital Database (SOTER) for South Africa (Dijkshoorn, 2003).

Model inputs were interpolated onto the topographic data at a resolution of 30 m via a nearest neighbour algorithm using ARCGIS 10.3 and Spatial Analyst (Environmental Systems Research Institute (ESRI), 2010). In order to run the model for the whole of South Africa the model input layers were clipped to the catchment scale and then further clipped to the quaternary scale in order to accommodate the model which was designed to be run on much smaller catchments. After clipping the input layers to the desired catchment units, the raster files were converted to ascii files for input to the SCIMAP model.

The SCIMAP model is run in the System for Automated Geoscientific Analyses (SAGA) an open source geographic information computer program (Conrad et al., 2015). The SCIMAP modelling framework consists of five main steps (Figure 1).

For this study the framework was adapted from measuring fine sediment risk (Reaney, 2011), to measuring flood receiving areas. In step one, the flood generation potential for each land cover class is determined by multiplying the energy available to generate runoff by the resistance to runoff generation. In the model the energy available to generate runoff is assumed to be positively related to the upslope contributing area and the local slope which is both derived from the 30 m DEM (Reaney, 2011). To measure the resistance to runoff generated, we adapted the model and used the Natural Resources Conservation Services (NRCS) runoff curve number to infer a runoff weighting upon each land cover class.

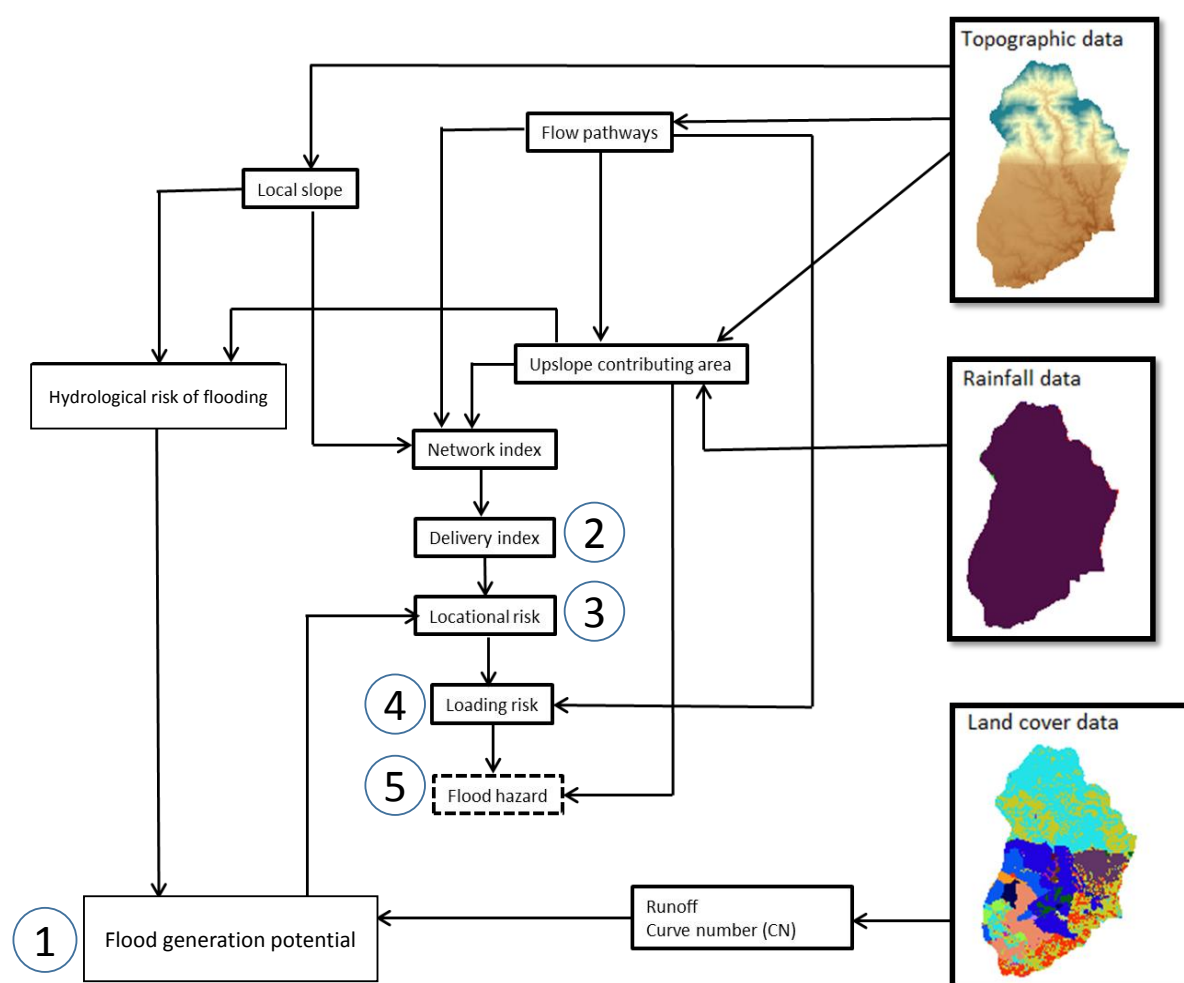


Figure 1: Diagram summarising the steps and inputs in the calculation of the flood hazard.

The NRCS runoff curve number (CN) was selected as it is used as a core component of many of the more sophisticated hydrologic models, yet requires only readily available data (Du et al., 2012; Grimaldi et al., 2013). It is an index developed by the United States Department of Agriculture in 1972 and is a function of land cover type and hydrologic soil group (USDA, 1986). It is a numerical description (0-100) of the impermeability of the land in a watershed. The runoff curve number provides a first approximation of the potential for surface runoff, with greater curve numbers indicating a greater proportion of surface runoff and consequently lower infiltration, and smaller curve numbers indicating low runoff and consequently higher infiltration (Melenti et al., 2011). The runoff curve number (CN) is a dimensionless number, which is reasonably robust, and therefore, lends itself to be incorporated into the SCIMAP framework. The use of run off curve numbers is controversial as it has been used in the past without consideration of the limitation of the approach (Garen and Moore, 2005). Here the approach is used at a watershed scale to serve as a weighting based on the land cover and soil type. For the generation of the curve numbers, data inputs comprises a soil map of soil



types and textures as well as a land cover map. The soil map was clipped to the study area using ArcGIS Desktop 10.3. Based on this map, hydrological soil groups were identified based on their soil texture and permeability. Soils were classified into four hydrological soil groups (A, B, C, and D) (Table 1).

Table 1: Hydrologic soil groups identified from soil textures

Soil group	Nature/description	Soil texture
A	Well drained (high infiltration).	Sand, loamy sand, or sandy loam.
B	Moderate to well-drained (moderate infiltration).	Silt loam or loam.
C	Poor to moderately well drained (low infiltration).	Sandy clay loam.
D	Poorly drained very low infiltration.	Clay loam, silty clay loam, sandy clay, silty clay or clay.

The resulting hydrological soils group map was intersected with the National Land Cover (NLC) 2000 of South Africa, to form a land cover hydrological soils group map using ArcGIS Desktop 10.3. The curve number for each polygon was determined using an existing curve number database created by Thomas (2015) using the NLC 2000 of South-Africa. For the purposes of the SCIMAP model, curve numbers were rescaled from 0-100 to 0-1 by dividing by 100. In step two the delivery index is determined based on a network index similar to the topographic wetness index of Beven and Kirkby (1978). The network index is based on the assumption that as the watershed wets up, it becomes increasingly connected as points that were previously disconnected start to generate and transmit runoff, connecting the upslope areas of the watershed to the river channel (Lane et al., 2009). At this point each location in the watershed has a flood generation potential and a delivery index which, in step 3, are multiplied together to produce the locational risk. In step 4 the locational risk is routed through to the river network using the flow pathways previously generated from the DEM to produce a loading risk. In the fifth and final step the upslope contributing area derived from rainfall and topographic data is added to the loading risk to produce a flood hazard concentration. The results represent a relative ranking of flood receiving or hazard areas. Model outputs were exported to ArcGIS and merged up to the primary catchment level using the spatial analyst tool. Zonal statistics were run on the primary catchments to determine the mean flood hazard per settlement.



3.4 Flood exposure

We used vertical overland flow distance to the channel network as a proxy for the flood exposure. Vertical overland flow distance is based on vertical distance between cell elevations and the elevations calculated for the channel network in that cell. So, non-channel cells will be assigned a value which represents the elevation difference between those cells and the elevation of the nearest channel. The distance is expressed in the same units as the heights and cell size values from the DEM grid which, in this case was metres. The vertical overland flow distance was calculated using the open source SAGA GIS software (Olaya, 2004) based on the inputs of the 30 m DEM and channel network information derived from the SCIMAP model outputs. Using the extract by attribute function in the spatial analyst tool in ArcGIS, areas with an elevation different of ≤ 10 m were extracted. Zonal statistics were run on the extracted layers to determine the sum of the areas with a vertical overland distance of less or equal to 10 m for each settlement. The resulting values were then divided by the total area of the settlement and then multiplied by 100 to derive the percentage of each settlement situated ≤ 10 m above the nearest river channel. The output was then intersected with the National Land Cover 2013-14 (GTI, 2015) to determine the land cover types present in the areas ≤ 10 m above the channel network and thus potentially exposed to floods.

4 RESULTS

4.1 Climate and hydrological characteristics

The 50-year return period daily rainfall as used in the flood hazard modelling shows an interesting distribution across South Africa (Figure 3). It is however important to look at the general patterns rather than the individual catchments because the values are based on weather station observations and are strongly influenced by the length of the observed records, location and density of the weather stations. This is especially true in the western interior where there are very few weather stations.

The data show that the 50-year interval one day design rainfall is between 40 and 95 mm across the whole of South Africa, Lesotho and Swaziland, with about 33% of the total area falling in this class (Figure 2). Nearly 42% would get between 95 and 131 mm, 17% between 131 and 174 mm, and about 8% more than 174 mm. The highest values occur primarily along

the eastern coast of South Africa, from East London through to the Mozambique border, well as in parts of Mpumalanga and Limpopo, but also at various locations in the interior. So, most of the eastern part of the country can expect to have more than 130 mm, and parts more than 230 mm of rainfall in a single day about once every 50 years. This is a considerable volume of water as 130 mm equates to 1 300 m³/ha and, if this falls on a 10 000 ha catchment, it would amount to 130 million m³ of water, enough to fill a large dam. To put this in perspective, only 15% of South Africa's dams have a capacity of 100 million m³ or more. However, please note that some of the rainfall is likely to be absorbed by the soil or captured behind dams, so the daily rainfall cannot simply be converted to a flood volume. The volume calculated above just gives an indication. However, if the rainfall intensity is high (say >20 mm per hour) then most of that rainfall will become floodwater because the soils and other permeable surfaces simply cannot absorb that amount of water. If the soils were already moist or wet due to some previous and recent rainfall, or if the high rainfall continues for many hours or days, then most of the rainfall will become flood water.

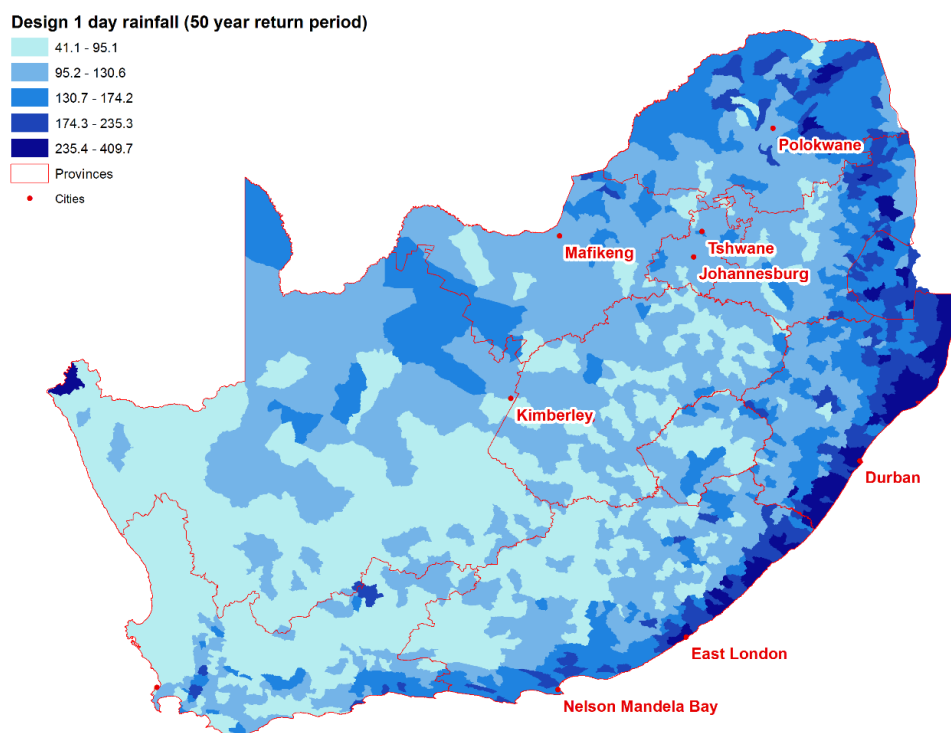


Figure 2: 50-year return period design on day (daily) rainfall for South Africa (Schulze et al., 2008). The class intervals are based on a geometric scale to reduce the influence of extreme values

Another way to assess the rainfall-related flood hazard is to use modelled river flows which are based on the rainfall records, other climatic inputs and biophysical characteristics of the catchments. This modelling incorporates a number of factors that will determine how an area of land responds to rainfall (Schulze et al., 2008; Smithers and Schulze, 2003). For example

it can include estimates of the ability of the soils to absorb that rainfall as the rainfall event progresses and so gives an idea of the flood volumes that can be expected. This assessment shows that the high stormflows mainly occur in the eastern half of the region, but also in the southern parts from Mossel Bay to Nelson Mandela Bay, and in the Boland and Groot Winterhoek Mountains (Figure 3).

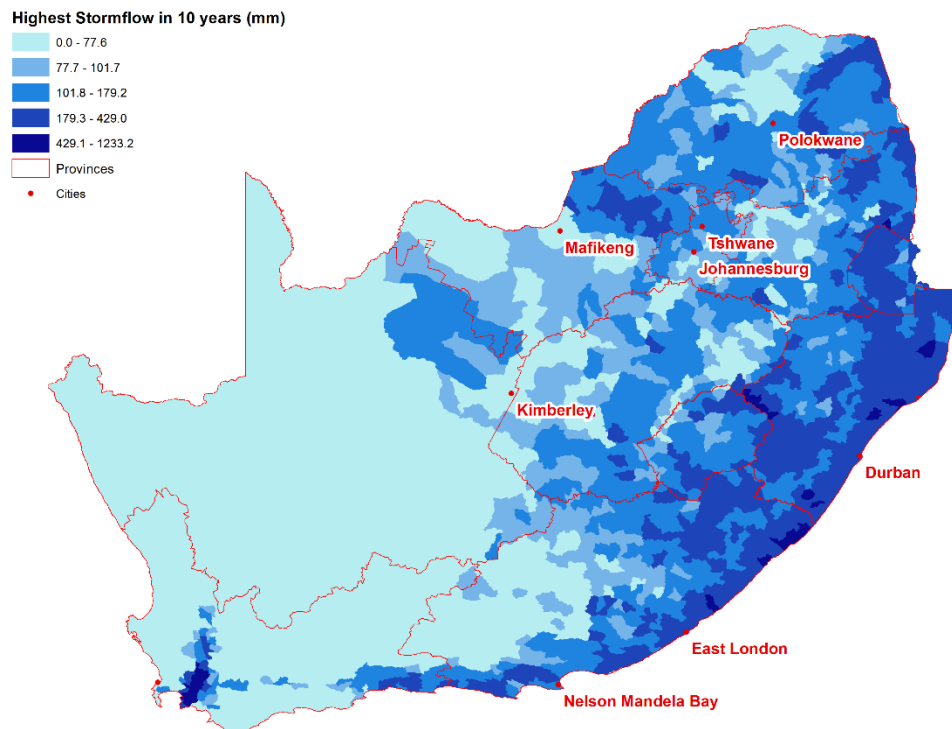


Figure 3: The modelled highest daily stormflow in a 10 year period (Schulze et al., 2008). The class intervals are based on a geometric scale to reduce the influence of extreme values.

This map makes it clear that settlements in the eastern part of South Africa, or Lesotho and Swaziland, can expect high stormflows, especially those near the coast in the Eastern Cape, in most of KwaZulu-Natal, in the Boland and the Garden Route. The variability between years in the stormflows highlights an important characteristic of the rainfall, and thus the stormflows in the western part of South Africa, namely its very high variability between years (Figure 4). The map shows that while the highest stormflow in 10 years may be low in the western interior, the variability is high and indicates that sudden floods are still possible, albeit very infrequently, probably at recurrence intervals greater than 1 in 50 years. There are examples of these periodic floods on record, driven by intense rainfall and triggering flash floods in the ephemeral rivers which drain these landscapes because these arid landscapes cannot absorb the rainwater. Some, such as the Laingsburg floods, get into the news but most have little impact on settlements and are probably not reported. Conversely, all the areas that get relatively

reliable and high rainfall every year, show a low variability between years such as the Boland Mountains and parts of the Eastern Cape, KwaZulu-Natal and the Free State but the north-eastern Free State has high variability. Some of the drier parts of Lesotho and Maputaland also have high variability in their stormflows. The class intervals are based on a geometric scale to reduce the influence of extreme values.

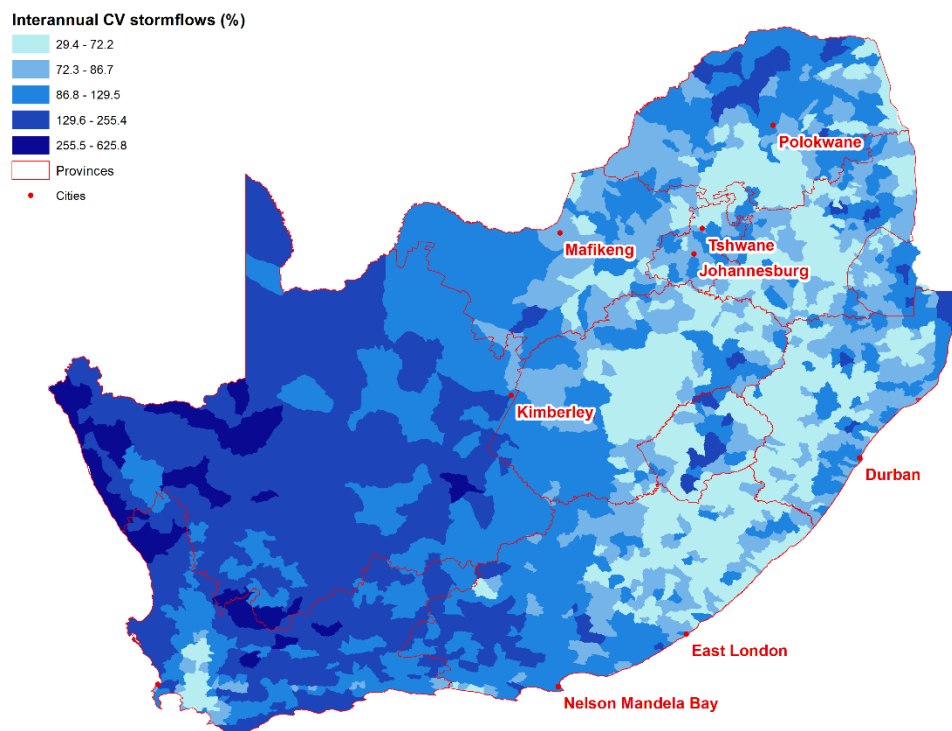


Figure 4: The variability in the stormflow between years (inter-annual) as a percentage of the mean stormflow (i.e. the Coefficient of Variation as a percentage) (Schulze et al., 2008).

Another useful measure of the flood risk is based on the observed floods and the ratio of the flood discharge (m^3/sec) to the normal mean annual discharge, also known as the K-ratio (Kovács, 1988; Smithers, 2012). Essentially the K-ratio estimates how many times greater the flood peak is than the typical river flow and it has been estimated for South Africa, Lesotho and Swaziland, albeit some time ago (Kovács, 1988). The distribution of the ratio across the region shows some similarities with the design rainfall and flood information summarised above, with higher values found in the catchments in the southern and eastern parts and lower values in the western interior (**Error! Reference source not found.**5). The highest ratios were found in the coastal catchments from Nelson Mandela Bay through to north of Durban K-ratio = 5.4) with northern KwaZulu-Natal the highest at 5.6.

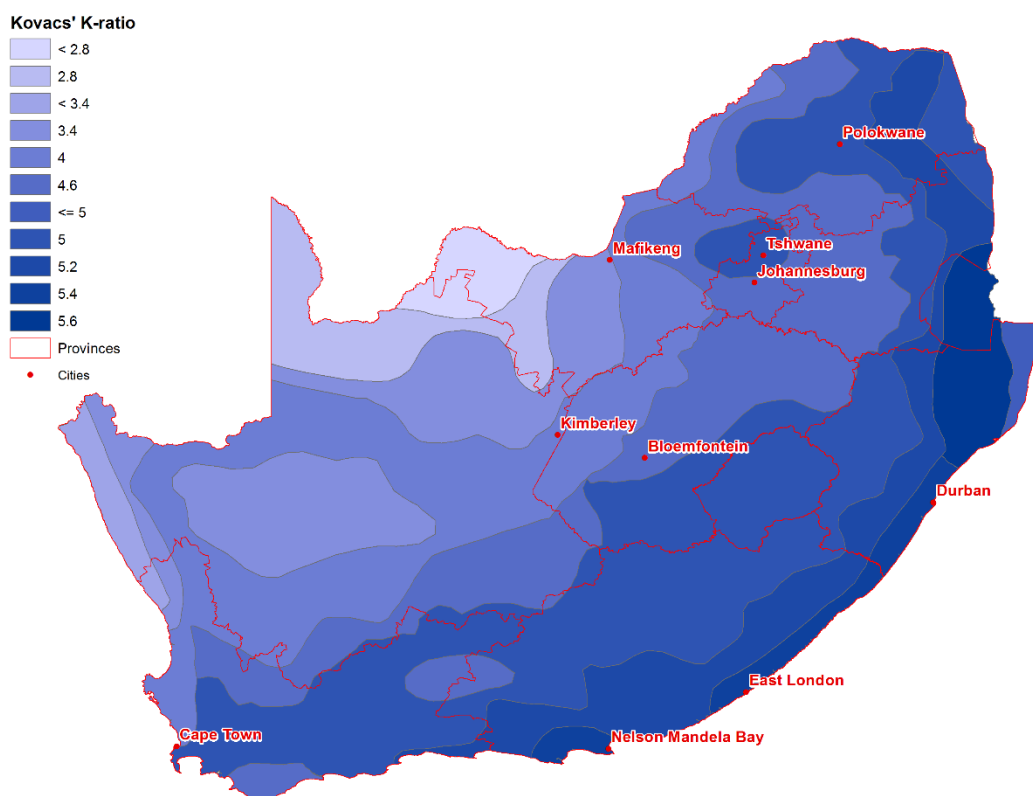


Figure 5: The regionalised K-ratio i.e. the ratio of the flood peak in m³/sec to the average annual flow in m³/sec for catchments in South Africa, Lesotho and Swaziland (Kovács, 1988). Digital version supplied by the Aurecon Group (Andre Görgens personal comm)

4.2 Projected increases in extreme daily rainfall

Although there are uncertainties about the changes in rainfall under future climates with different models and different emission scenarios having different outcomes, there is general agreement that rainfall intensities (the amount of rainfall in a given period of time) will increase. So, under future climates it is likely that the design rainfall (Figure 2) will increase and that the volumes of storm runoff will increase, leading to increased occurrence of floods. One way of assessing the degree of the change is to compare future rainfall extremes (e.g. 95th percentile of daily rainfall) with those under the current rainfall (1971-2000) based on the global climate model outputs. This comparison indicates that in the near-future (2021- 2050) the extreme daily rainfall will increase in many parts of the country, particularly over the Highveld and northern Drakensberg, and in a broad belt along the south-eastern and eastern coast (Figure 6). The western and south-western regions are likely to experience a decrease, including the winter rainfall region. This is consistent with an expectation that increasing temperatures will

increase the intensity of the convection rainfall systems (e.g. thunderstorms) which are characteristic of this part of the country (Dedekind et al., 2016).

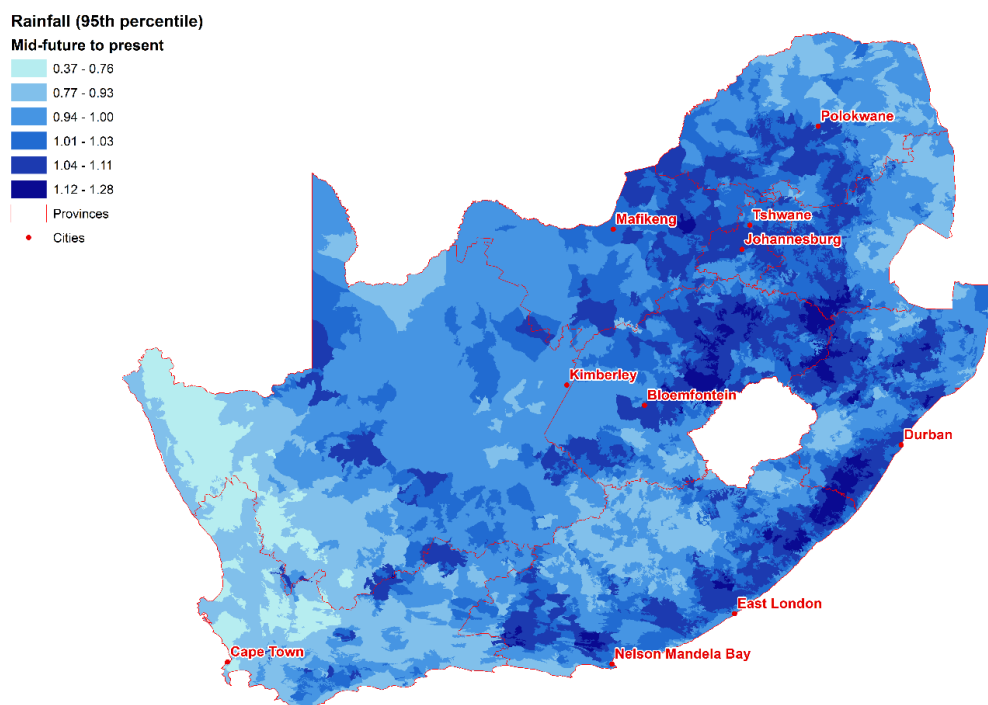


Figure 6: The mean ratio of the near-future (2021-2050) and current (1971-2000) extreme daily rainfall (95th percentiles) for each quinary catchment. Values greater than 1.0 indicate an increase in the extreme daily rainfall.

In the far future (2070-2099) the same general pattern is evident with increases in the extreme daily rainfall in the central, eastern and northern parts of the country and decreases in the west and south-western parts, except for the coastal Agulhas to George area where there will be an increase (Figure 7). Given the flooding and extensive flood damage caused in Gauteng and parts of the adjacent provinces in recent years, these projections suggest that investment is needed to mitigate and adapt to these conditions. This will include investment in restoring ecological infrastructure, upgrading built infrastructure in combination with green infrastructure (e.g. water sensitive urban design) and ensuring that settlements and infrastructure are removed from high flood risk areas.

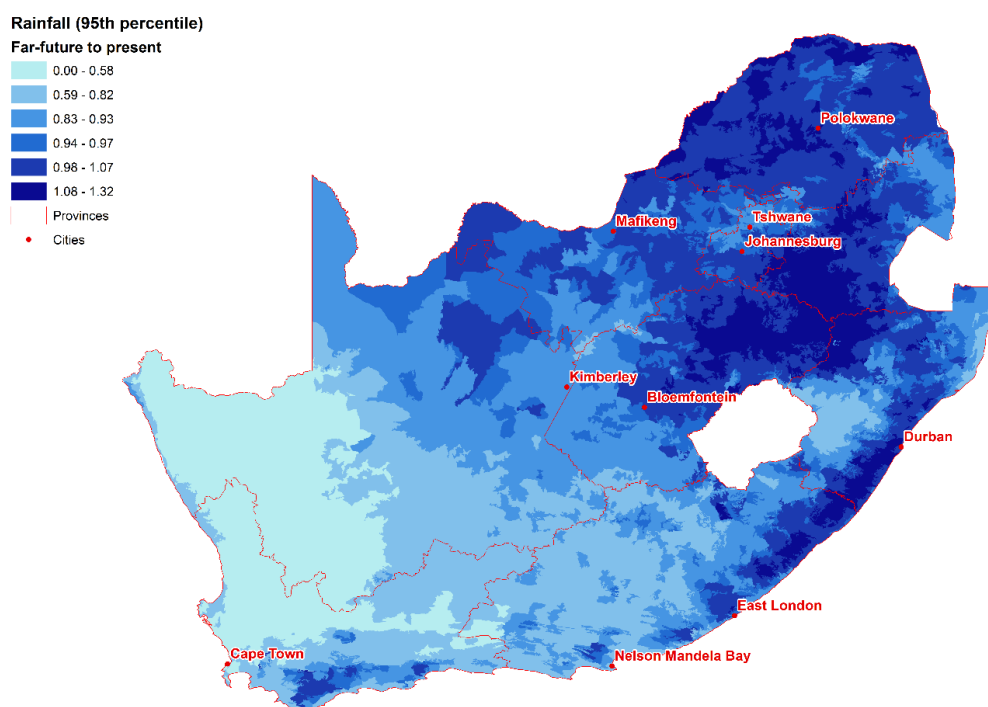


Figure 7: The mean ratio of the near-future (2070-2099) and current (1971-2000) extreme daily rainfall (95th percentiles) for each quinary catchment. Values greater than 1.0 indicate an increase in the extreme daily rainfall.

4.3 Flood Hazard Index

The Flood Hazard Index (FHI), which is based on the catchment characteristics and design rainfall, was averaged at the quinary catchment level and the classes were defined using the standard deviations as the distribution of the FHI values followed a normal distribution.

Two catchment areas are shown in detail to illustrate the outputs of the model. The first shows the quinary sub-catchments in the primary catchment U which includes all the river systems between the Mtentweni River, north of Port Shepstone, and the Zinkwazi River, just south of the Tugela (Figure 8). A very high FHI is found in the headwaters of the uMlazi River just south of Pietermaritzburg and forms part of a band of high FHI which runs from north to south in this catchment. The upper catchment of the Lovu River in the Drakensberg foothills also has an area of high FHI. The lowest FHI values are found in catchments on the southern boundary and low values are found along the coast north and south of Durban.

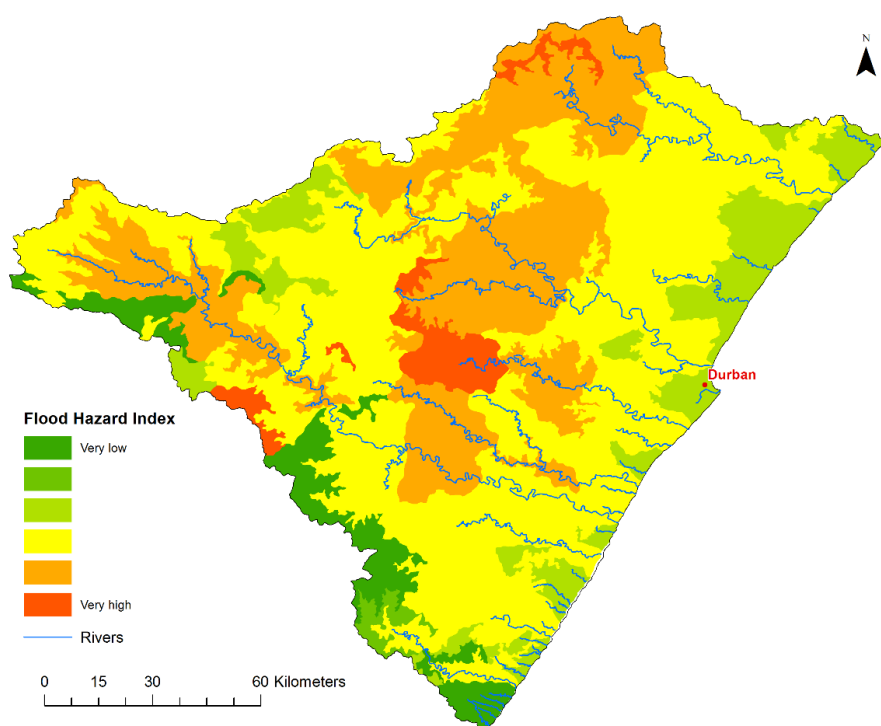


Figure 8: The Flood Hazard Index calculated by the SCIMAP model for the primary catchment area U showing the mean values per quinary catchment. Class intervals based on the standard deviation of the mean values per quinary catchment.

In the case of the Inkomati catchment, the very high FHI hazard is found at several points in the valley of the Crocodile River, particularly to the east of KaNyamazane. A large portion of the Crocodile River catchment also has a high FHI. There is also a relatively high FHI in the Lowveld in the eastern part of the catchment, much of which is within the Kruger National Park (Figure 9). The Highveld in the upper Komati catchment has a low to very low FHI, as do areas in the north of this catchment. The white area in the south of the catchment is a portion of Swaziland, which was not included in this study.

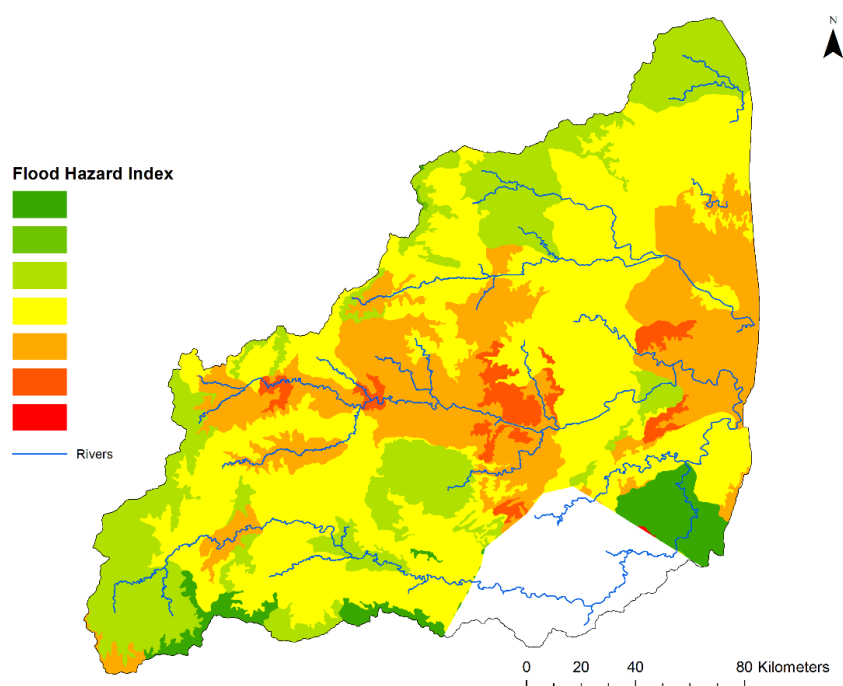


Figure 9: The mean flood hazard calculated by the SCIMAP model for the primary catchment area X (Inkomati River System) for each quinary. Class intervals based on the standard deviation of the mean values per quinary catchment.

When assessed at the national level, the FHI is rated medium for much of the country, with Namaqualand, the Kalahari, parts of the Karoo, the Limpopo valley and the Zululand coast having a low to very low FHI (Figure 10). Very high FHI values are found in:

- The Sneeuwerge north and west of Cradock in the catchments of the Pauls, Wilgerboom and Kwaai Rivers – all tributaries of the Great Fish River
- The Mbhashe River valley near Bashee Bridge
- A region of the Eastern Cape extending from the central Thina and Mzimvubu River valleys (south-east of Mount Frere) through to Donnybrook in KwaZulu-Natal
- The uMlazi River valley
- The central Tugela River valley, the uMfolozi near Ulundi
- The Drakensberg escarpment where it crosses the Crocodile and Olifants River valleys, and
- The Soutpansberg.

The FHI for the Cape mountains is generally relatively low at the national level, but there are areas with a higher FHI in these mountains. The small portion of the Richtersveld estimated to be very high FHI largely because it is mountainous and the land cover is predominantly bare ground, but it is essentially uninhabited, giving it a low flood risk.

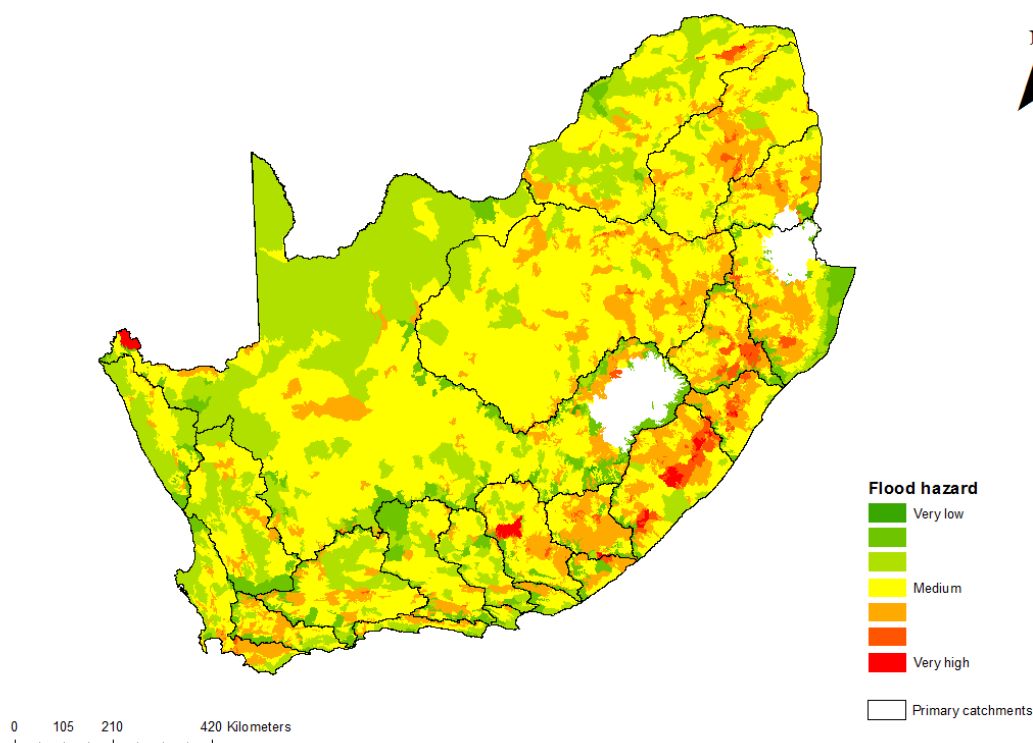


Figure 10: Mean Flood Hazard Index (FHI) per quinary (5th order) catchment based on the SCIMAP model run at the secondary catchment level. Class intervals based on the standard deviation of the mean FHI for the quinary catchments.

4.4 Cederberg and Dihlabeng Local Municipalities

The Cederberg Municipality is situated in the north-western part of the Western Cape Province and borders on the Northern Cape (Figure 11). Both Citrusdal and Clanwilliam are situated in the Olifants River valley and near or next to the river which has its source to the south, and outside of, the municipality. The high elevation area to the east of them is the Cederberg Mountains which have relatively high rainfall. The Piekenierskloof Mountains west of the Olifants River valley separate the valley from the relatively flat coastal plains. Clanwilliam and Citrusdal in the Olifants River valley, Graafwater next to the Jakkals River, and Leipoldtville on the Langvlei River, all have a moderate flood hazard. The other settlements all have a low hazard. Citrusdal has an additional source of flood hazard because it is next to the Olifants River which has its source outside the municipality, but Clanwilliam is not situated next to this large river and so does not have this additional hazard.

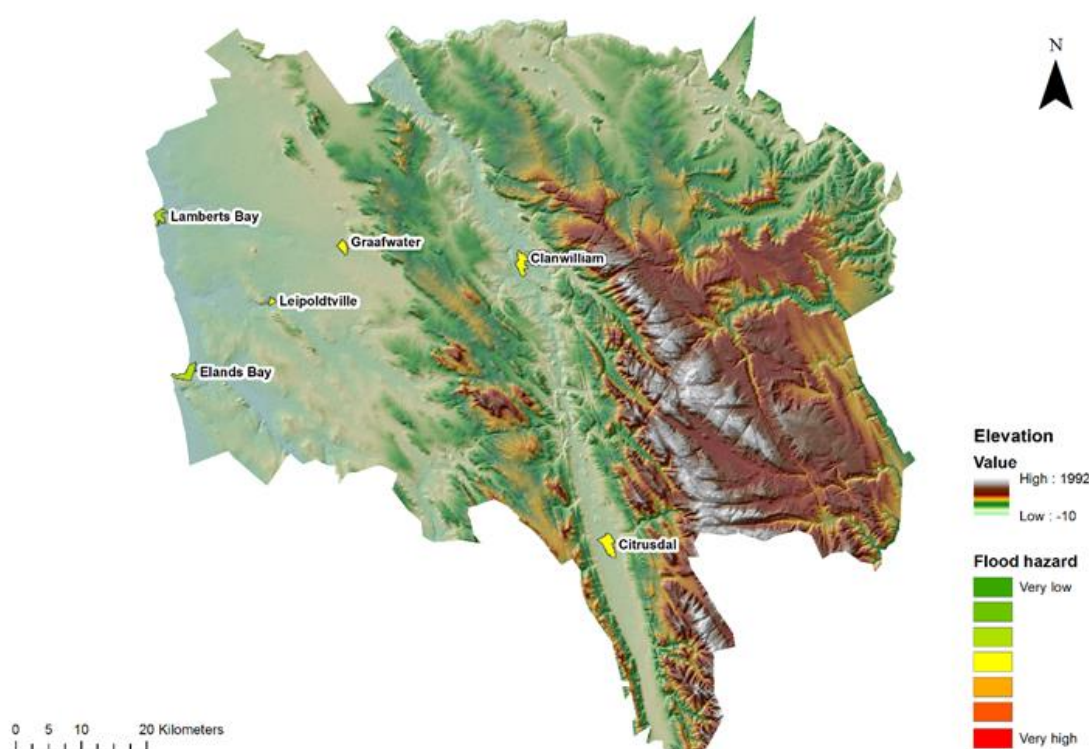


Figure 11: The Cederberg Municipality showing the settlements and the flood hazard modelled for each one based on the SCIMAP model.

The statistics on the exposure do show though that portions of every one of these settlements are situated within 10 m above the estimated river level. Both Clanwilliam and Elands Bay have low proportions exposed, but Citrusdal, Lamberts Bay, Graafwater and Leipoldtville have large proportions of their settlements exposed. Lamberts Bay is situated on the coast and next to a broad estuary so the river water is unlikely to rise to 10 m because it will be able to flow out of the river mouth. The same applies to Elands Bay. Graafwater is next to the Jakkals River but it has a relatively small catchment so the likelihood of a flood raising water levels in the river valley by 10 m is very low.

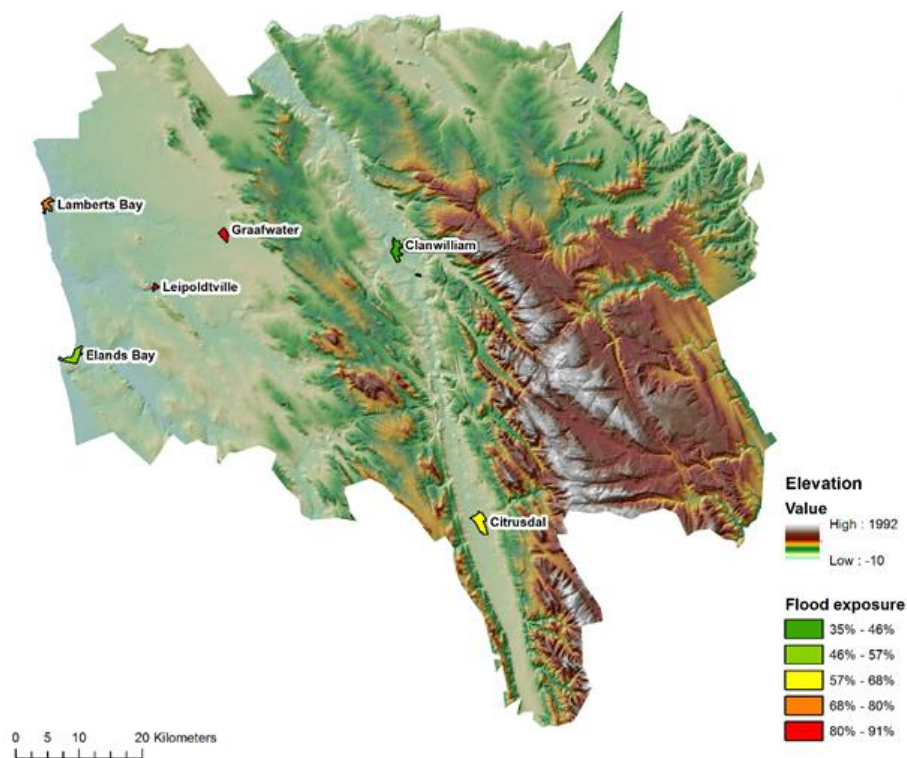


Figure 12: The proportions of the different settlements that are exposed (i.e. situated within 10 m of the estimated river level).

Most of the exposed areas in each of these settlements is under natural vegetation, and thus have a low risk, except for Clanwilliam and Lamberts Bay where a substantial proportion of the exposed area is urban (formal or informal) (Figure 13). In the case of Clanwilliam, the Jan Dissels River lies on the eastern side of Clanwilliam and a large proportion exposed area (<10 m above the river level) is urban, creating a potential flood risk.

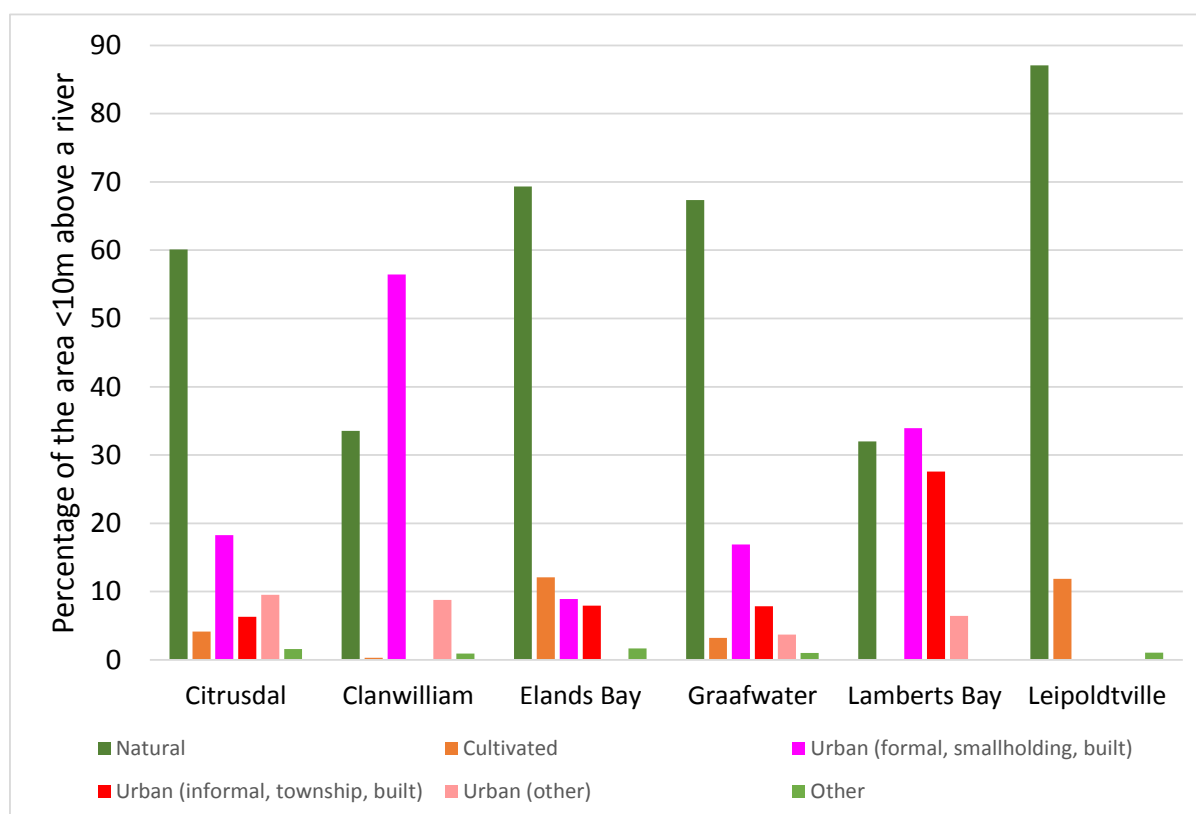


Figure 13: The land cover in the areas situated less than 10 m above the level of the rivers next to or passing through the settlements. Classes in the 2013/14 land cover (GTI, 2015) were combined into the main ones from the risk perspective

The higher rainfall areas of the Cederberg and the area immediately south of Citrusdal have the highest 1-day (1 in 50 year) design rainfall in the municipality (Figure 14). The low rainfall areas of the West Coast plains north of Elands Bay and the Tankwa Karoo in the far east of the municipality also have low design rainfall.

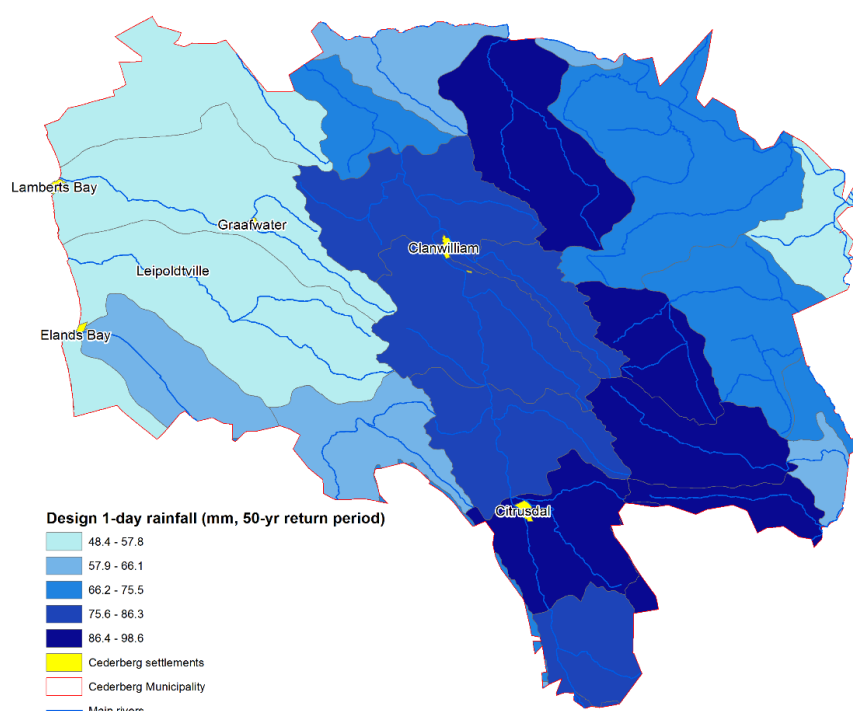


Figure 14: Cederberg Municipality showing the 1-day design rainfall (50 year return period) for each of the quaternary catchments. Data from Schulze et al. (2008).

The FHI also emphasises the relatively high values in the catchments including, and upstream of, Citrusdal. This is primarily the result of two factors in combination: rugged mountains with relatively high rainfall (Figure 15) and typically shallow soils. The very high FHI in the south-eastern part of the municipality is due to an extensive area of nearly bare rock which is formed by the top of the Hottentotsberg which borders on the Tankwa Karoo.

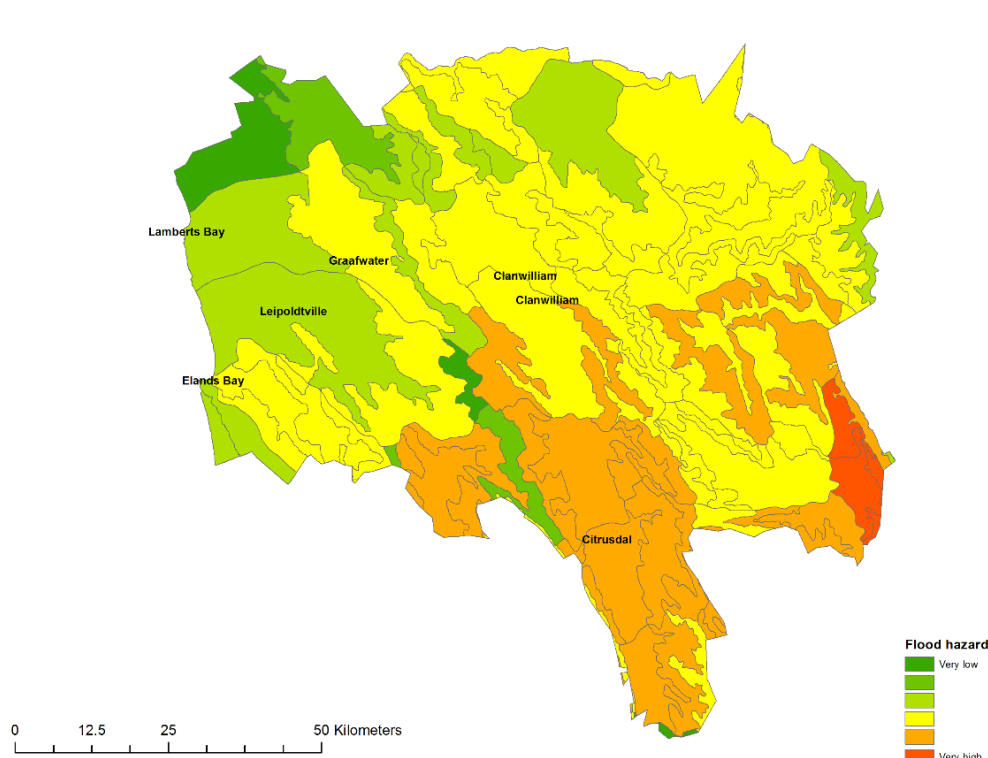


Figure 15: The Cederberg Municipality showing the mean FHI estimated by the SCIMAP model for the quinary catchments in this area.

The Dihlabeng Municipality is situated in the north-eastern Free State where its southern boundary borders on Lesotho with the international boundary following the Caledon River (Figure 16). The northern part consists of relatively flat plains but the southern parts have higher mountains in the form of the Witteberge east of Rosendal, the Rooiberge north-west of Fouriesburg and an outlier of the Maluti Mountains in the south-eastern corner. The town of Clarens has a moderate to high flood hazard being situated in a relatively steep-sided valley in the Rooiberge and the adjacent Kgubetswana township has a high flood hazard. Paul Roux and Rosendal also have a moderate to high flood hazard as a result of being situated on rivers which have steep headwater catchments. Bethlehem and Fouriesburg have a moderate flood hazard.

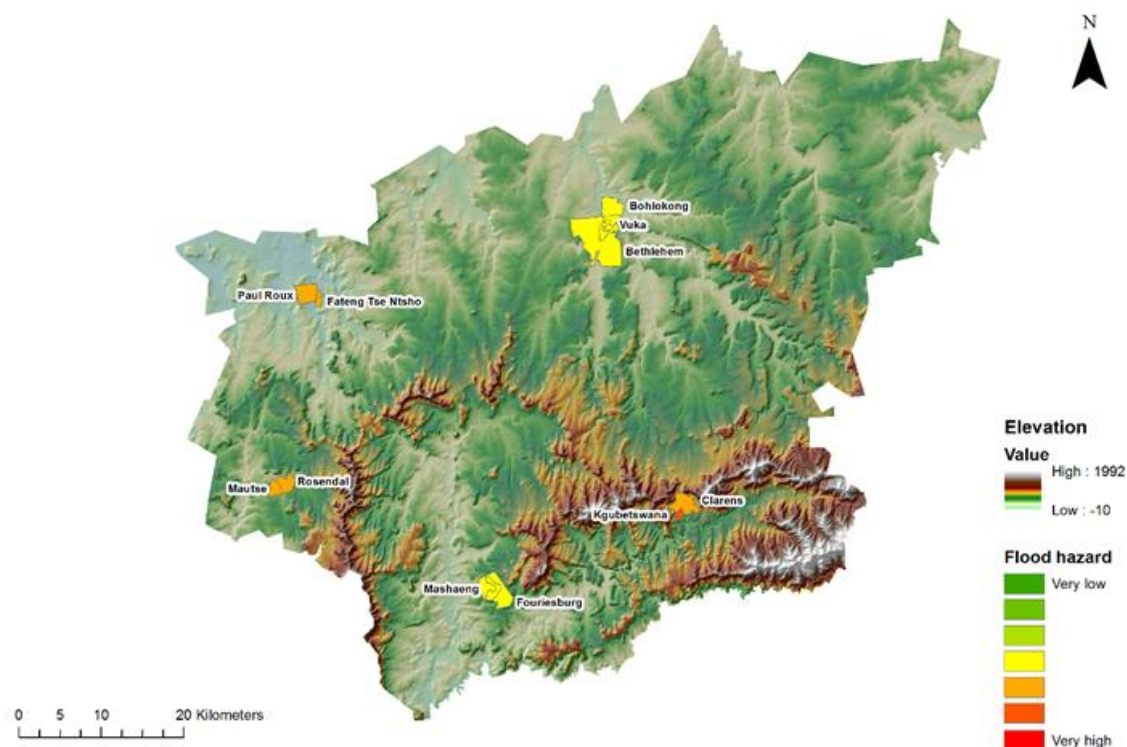


Figure 16: Dihlabeng Municipality showing the settlements and the flood hazard modelled for each one based on the SCIMAP model.

The settlements differ also in the proportion that is exposed to flooding (i.e. <10 m above the estimated elevation of the closest river with Fouriesburg, Mashaeng and Kgubetswana have the smallest exposure, followed by Clarens and Bohlokong (Figure 17). Vuka is the most exposed followed by Bethlehem, Paul Roux and Fateng Tse Ntsho, Rosendal and Mautse. In Bethlehem the formal urban areas are exposed, but for all the others (Vuka, Fateng Tse Ntsho, Mautse) the exposed urban areas are townships (Figure 18). These findings must be seen in context. Most of these settlements are near the headwaters of these catchments so the likelihood that the river water level could rise by 10 m is low. Vuka is probably the most exposed because it is relatively far downstream on the Liebenbergsvlei River so intense rainfall in the upstream catchment could lead to flooding. Dihlabeng Municipality is located in an area where the rainfall intensity could increase in the future (Figure 6) so we suggest that the potential for flooding in the areas with the greatest exposure should be assessed.

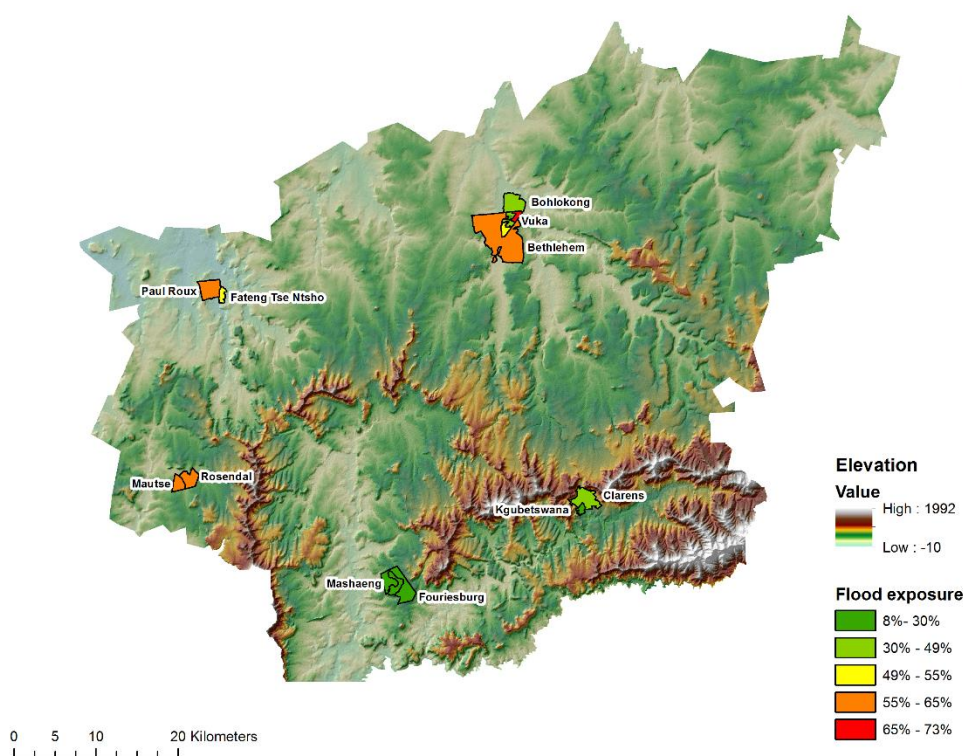


Figure 17: The proportions of the different settlements that are exposed (i.e. situated within 10 m of the estimated river level).

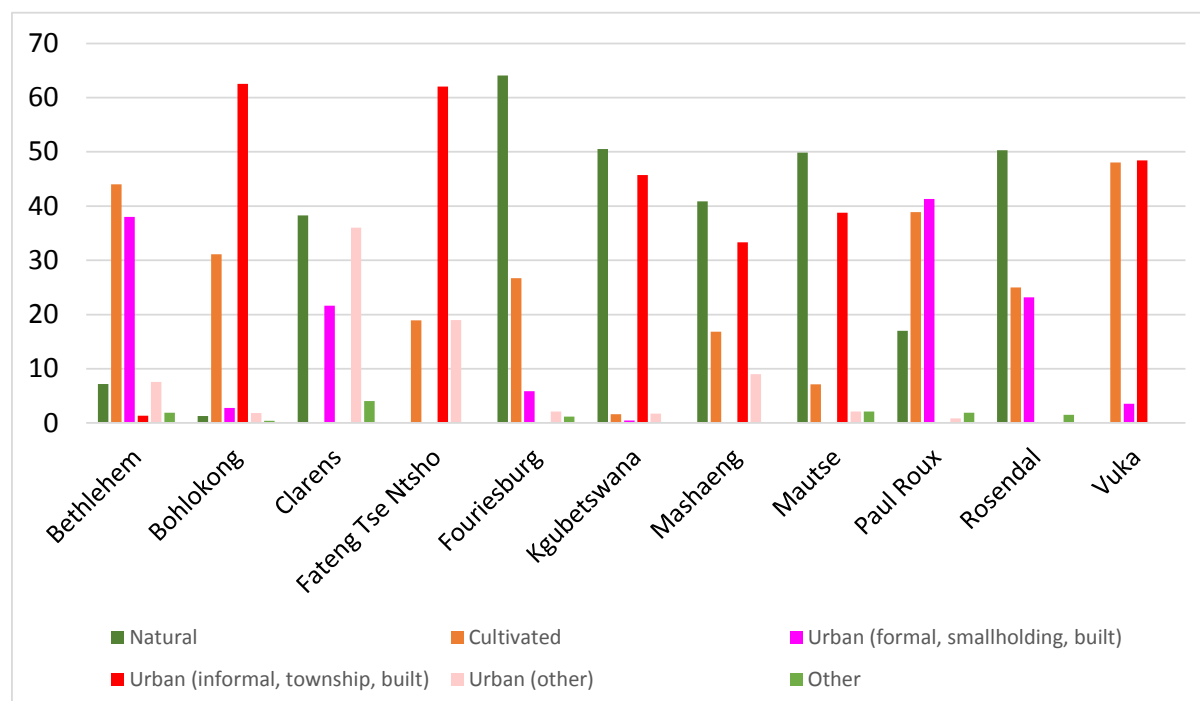


Figure 18: The land cover in the areas situated less than 10 m above the level of the rivers next to or passing through the settlements. Classes in the 2013/14 land cover (GTI, 2015) were combined into the main ones from the risk perspective.

The highest 1-day (1 in 50 year) design rainfall in the Dihlabeng Municipality occurs in a band running from west to east which includes the Little Caledon River valley, the mountain ranges to the north and south of it, and the towns of Clarens and Fouriesburg (Figure 19). Paul Roux and Bethlehem both have higher design rainfall than the remaining settlements.

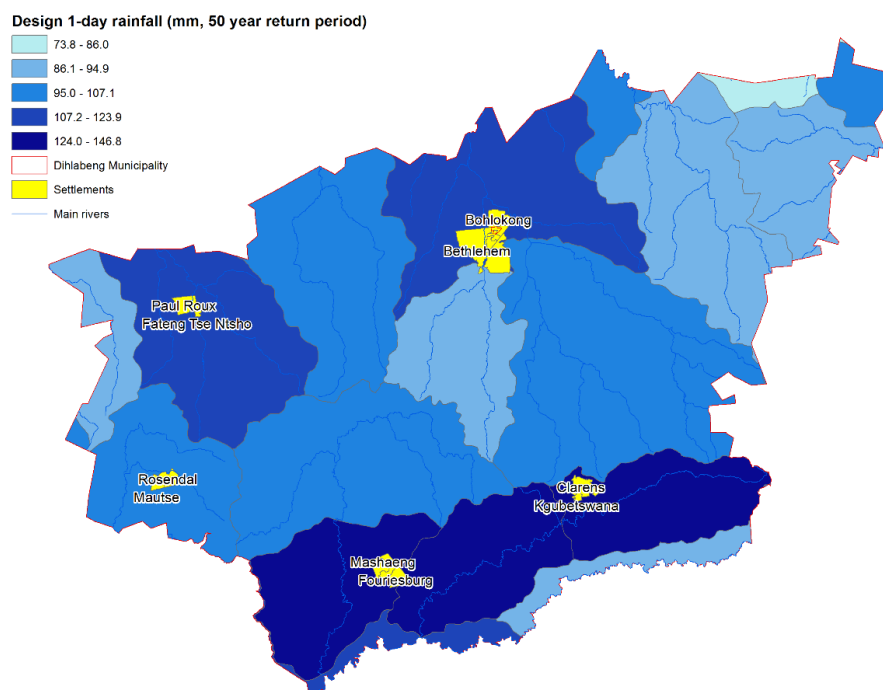


Figure 19: Dihlabeng Municipality showing the 1-day design rainfall (50 year return period) for each of the quaternary catchments. Data from Schulze et al. (2008).

Much of the Dihlabeng Municipality falls into a high FHI class, especially the western part of the Little Caledon River valley and an area running northwards from there (Figure 20). Interestingly, some of the areas likely to experience relatively high rainfalls (Figure 29) have a relatively low FHI, but the area to the east of Fouriesburg has both a relatively high daily rainfall and a relatively high FHI.

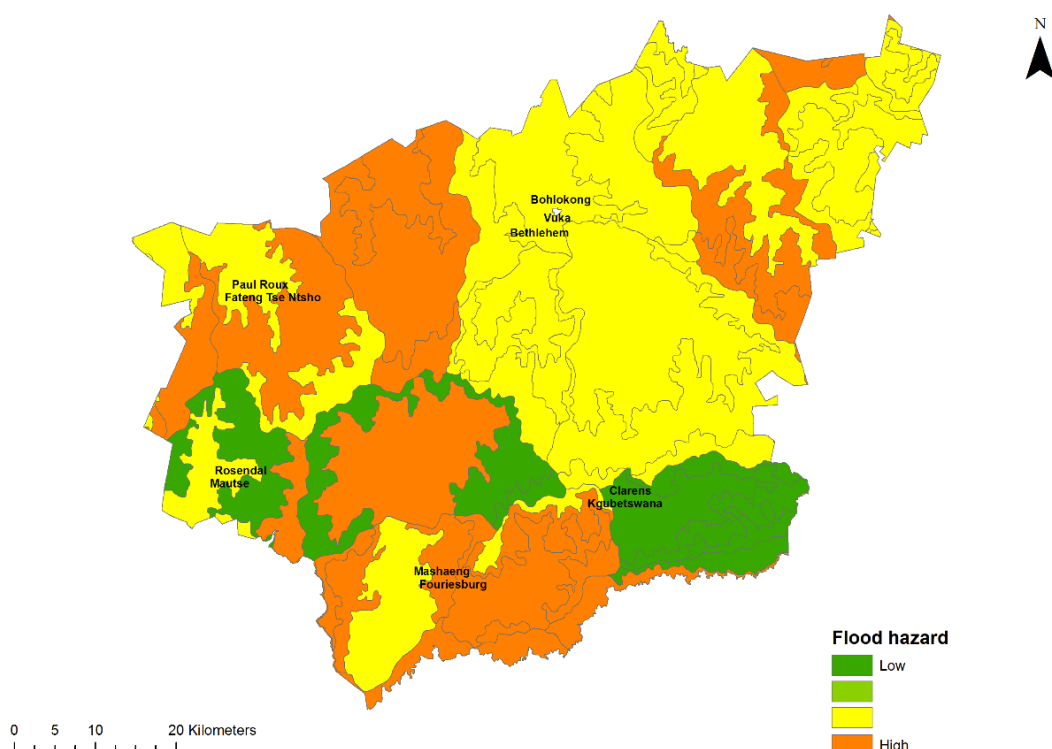


Figure 20: The Dihlabeng Municipality showing the mean FHI estimated by the SCIMAP model for the quinary catchments in this area. Note that the class intervals differ a little from those in the national level map.

5 CONCLUSION

There is a general pattern in the distribution of the intensity of the design rainfall, stormflows, K-ratio and the Flood Hazard Index. All of them have relatively high values in the eastern part and southern parts of South Africa. This is not surprising as a key driver of the flood hazard is the rainfall, and these are also the areas of the country that get the highest rainfalls, whether daily, monthly or annually. Although it does not have such high rainfall, much of Limpopo Province is likely to experience high intensity daily rainfall (Figure 2) and also has a relatively high K-ratio (Figure 5), indicating a relatively high flood hazard. The northern and eastern parts of the country, including the coastal regions, are also likely to experience an increase in the intensity of the daily rainfall in future, a trend which will interact with the other factors to increase flood risks (Figure 6).

This is only an initial assessment aimed at providing an overview of the relative flood hazards and risks for a wide range of settlements across the country. It needs to be supplemented with a more detailed local authority and settlement level assessment of the hazards and risk incorporating local knowledge and consultation with the affected communities. Local



authorities which have settlements that are exposed to flood risks should initiate and conduct such assessments in a participatory and consultative fashion. The most effective way of reducing the flood risk is to recognise the fact that floods occur, that their severity is likely to increase, and that being adequately prepared is the best protective measure that can be taken. In some cases, settlements and other infrastructure may have to be moved out of flood-prone areas because prevention is better than attempting to repair the damage each time. Restoration of degraded land and wetlands, especially floodplain wetlands, so that the landscape can capture and store more rainwater for slow release can be an effective option (Bernhardt and Palmer, 2011; Dada et al., 2007; DEA and SANBI, 2016; Genthe et al., 2013; Johnson et al., 2016; Jones et al., 2018; McLaughlin and Cohen, 2013; Thorslund et al., 2017). Climate is not the only driver of flood risk, changes in land cover and land use upstream can also have significant impacts and it is critical that the downstream impacts are taken into account when assessing these developments.



6 REFERENCES

- Balica, S., Wright, N.G., 2010. Reducing the complexity of the flood vulnerability index. *Environ. Hazards* 9, 321–339.
- Balica, S.F., Popescu, I., Beevers, L., Wright, N.G., 2013. Parametric and physically based modelling techniques for flood risk and vulnerability assessment: A comparison. *Environ. Model. Softw.* 41, 84–92.
- Benjamin, M.A., 2008. Analysis of urban flood risk in low-cost settlements of George, Western Cape, South Africa: Investigating physical and social dimensions. Research Report prepared by Disaster Mitigation for Sustainable Livelihoods Programme, University of Cape Town for the National Disaster Management Centre, Pretoria.
- Bernhardt, E.S., Palmer, M.A., 2011. River restoration: the fuzzy logic of repairing reaches to reverse catchment scale degradation. *Ecol. Appl.* 21, 1926–1931.
- Beven, K., 1987. Towards the use of catchment geomorphology in flood frequency predictions. *Earth Surf. Process. Landforms* 12, 69–82.
- Beven, K., 2004. Robert E. Horton's perceptual model of infiltration processes. *Hydrol. Process.* 18, 3447–3460.
- Beven, K.J., Kirkby, M.J., 1978. A physically based, variable contributing area model of basin hydrology. *Hydrol. Sci.* 24, 43–69.
- Black, D., Turpie, J.K., 2016. Evaluating the cost-effectiveness of ecosystem-based adaptation: Kamiesberg wetlands case study. *South African J. Econ. Manag. Sci.* 19, 702–713.
- Bourne, A., Holness, S., Holden, P., Scorgie, S., Donatti, C.I., Midgley, G., 2016. A Socio-Ecological Approach for Identifying and Contextualising Spatial Ecosystem-Based Adaptation Priorities at the Sub-National Level. *PLoS One* 11, e0155235.
- Brocca, L., Melone, F., Moramarco, T., 2011. Distributed rainfall-runoff modelling for flood frequency estimation and flood forecasting. *Hydrol. Process.* 25, 2801–2813.
- Cheng, X., Shaw, S.B., Marjerison, R.D., Yearick, C.D., Degloria, S.D., Walter, M.T., 2014. Improving risk estimates of runoff producing areas: Formulating variable source areas as a bivariate process. *J. Environ. Manage.* 137C, 146–156.



- Chief Directorate Surveys and Mapping, 1990. Chief Directorate: Surveys and Mapping. Mobray.
- Coetzee, C., Van Niekerk, D., Raju, E., 2016. Emergent system behaviour as a tool for understanding disaster resilience: The case of Southern African subsistence agriculture. *Int. J. Disaster Risk Reduct.* 16, 115–122.
- Connor, R.F., Hiroki, K., 2005. Development of a method for assessing flood vulnerability. *Water Sci. Technol.* 51.
- Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., Böhner, J., 2015. System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. *Geosci. Model Dev.* 8, 1991–2007.
- Dada, R., Kotze, D., Ellery, W., Uys, M., 2007. WET-RoadMap. Report TT 321/07, Water Research Commission, Pretoria.
- Davis-Reddy, C.L., Vincent, K., 2017. Climate Risk and Vulnerability. A Handbook for Southern Africa (2nd ed.). CSIR, Pretoria, South Africa.
- DEA and SANBI, 2016. Strategic Framework and Overarching Implementation Plan for Ecosystem-Based Adaptation (EbA) in South Africa. Department of Environmental Affairs, Pretoria.
- Dearing, J.A., Wang, R., Zhang, K., Dyke, J.G., Haberl, H., Hossain, M.S., Langdon, P.G., Lenton, T.M., Raworth, K., Brown, S., Carstensen, J., Cole, M.J., Cornell, S.E., Dawson, T.P., Doncaster, C.P., Eigenbrod, F., Flörke, M., Jeffers, E., Mackay, A.W., Nykvist, B., Poppy, G.M., 2014. Safe and just operating spaces for regional social-ecological systems. *Glob. Environ. Chang.* 28, 227–238.
- Dedekind, Z., Engelbrecht, F.A., Merwe, J. van der, 2016. Model simulations of rainfall over southern Africa and its eastern escarpment. *Water SA*.
- Dijkshoorn, J.A., 2003. SOTER database for Southern Africa (SOTERSAF): Technical Report. International Soil Reference and Information Centre (ISRIC), Wageningen.
- Dilley, M., Chen, R.S., Deichmann, U., Lerner-Lam, A.L., Arnold, M., Agwe, J., Buys, P., Kjekstad, O., Lyon, B., Yetman, G., Lerner-Lam, A.L., Arnold, M., Agwe, J., Buys, P., Kjekstad, O., Lyon, B., Yetman, G., 2005. Natural Disaster Hotspots A Global Risk Analysis, World Bank. The International Bank for Reconstruction and Development and the World Bank and Columbia University, Washington DC.



- Du, J., Qian, L., Rui, H., Zuo, T., Zheng, D., Xu, Y., Xu, C.-Y., 2012. Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China. *J. Hydrol.* 464–465, 127–139.
- Els, Z., Van Niekerk, A., 2013. Data availability and requirements for flood hazard mapping. *Position IT Jan-Feb*, 40–46.
- Engelbrecht, C.J., Engelbrecht, F.A., Dyson, L.L., 2013. High-resolution model-projected changes in mid-tropospheric closed-lows and extreme rainfall events over southern Africa. *Int. J. Climatol.* 33, 173–187.
- Engelbrecht, F., Landman, W., Engelbrecht, C., Landman, S., Bopape, M., Roux, B., McGregor, J., Thatcher, M., 2011. Multi-scale climate modelling over Southern Africa using a variable-resolution global model. *Water SA* 37, 647–658.
- Environmental Systems Research Institute (ESRI), 2010. ArcGIS Desktop (ArcInfo) Software. Redlands, California, USA.
- Francou, J., Rodier, J.A., 1969. Essai de classification des crues maximales. In: *Floods and Their Computation: Proceedings of the Leningrad Symposium*. UNESCO, Paris, pp. 518–527.
- Garen, D.C., Moore, D.S., 2005. “Curve number hydrology in water quality modeling: Uses, abuses, and future directions,” - Reply to discussion. *J. Am. Water Resour. Assoc.* 41, 377–388.
- Genthe, B., Le Roux, W.J., Schachtschneider, K., Oberholster, P.J., Aneck-Hahn, N.H., Chamier, J., 2013. Health risk implications from simultaneous exposure to multiple environmental contaminants. *Ecotoxicol. Environ. Saf.* 93, 171–179.
- Gericke, O., du Plessis, J., 2013. Development of a customised design flood estimation tool to estimate floods in gauged and ungauged catchments. *Water SA* 39, 67–94.
- Glenday, J., 2015. Modeling the Hydrologic Impacts of Vegetation and Channel Network Change for a Semi-arid, Mountainous, Meso-scale Catchment: the Baviaanskloof, South Africa. PhD thesis, Bren School of Environmental Science & Management, University of California Santa Barbara.
- Görgens, A., 2007. Joint Peak-Volume (JPV) Design Flood Hydrographs for South Africa. Report No 1420/3/07, Water Research Commission, Pretoria.



- Grimaldi, S., Petroselli, a., Romano, N., 2013. Green-Ampt Curve-Number mixed procedure as an empirical tool for rainfall-runoff modelling in small and ungauged basins. *Hydrol. Process.* 27, 1253–1264.
- GTI, 2015. 2013 - 2014 South African National Land-Cover Dataset. Data User Report and MetaData. Version 05 (DEA Open Access), Geoterraimage, Pretoria.
- Hahn, C., Prasuhn, V., Stamm, C., Milledge, D.G., Schulin, R., 2014. A comparison of three simple approaches to identify critical areas for runoff and dissolved reactive phosphorus losses. *Hydrol. Earth Syst. Sci.* 18, 2975–2991.
- Haile, A.T., 2011. Regional Flood Frequency Analysis in Southern Africa. Faculty of Mathematics and Natural Sciences, University of Oslo, Oslo.
- Holloway, A., Fortune, G., Vimbai, C., 2010. RADAR Western Cape 2010. Risk and Development Annual Review. Cape Town.
- HRU, 1972. Design flood determination in South Africa. Report No. 1/72. Hydrological Research Unit, Department of Civil Engineering, University of the Witwatersrand, Johannesburg.
- IPCC, 2014. Summary for policymakers. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–32.
- Jencso, K.G., McGlynn, B.L., 2011. Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resour. Res.* 47, n/a-n/a.
- Johnson, F., White, C.J., van Dijk, A., Ekstrom, M., Evans, J.P., Jakob, D., Kiem, A.S., Leonard, M., Rouillard, A., Westra, S., 2016. Natural hazards in Australia: floods. *Clim. Change* 139, 21–35.
- Jones, C.N., Evenson, G.R., McLaughlin, D.L., Vanderhoof, M.K., Lang, M.W., McCarty, G.W., Golden, H.E., Lane, C.R., Alexander, L.C., 2018. Estimating restorable wetland water storage at landscape scales. *Hydrol. Process.* 32, 305–313.



- Kachroo, R.K., Mkhandi, S.H., Parida, B.P., 2000. Flood frequency analysis of southern Africa: I. Delineation of homogeneous regions. *Hydrol. Sci. J.* 45, 437–447.
- Knighton, J.O., Walter, M.T., 2016. Critical rainfall statistics for predicting watershed flood responses: rethinking the design storm concept. *Hydrol. Process.* 30, 3788–3803.
- Knoesen, D.M., Smithers, J.C., 2008. The development and assessment of a regionalised daily rainfall disaggregation model for South Africa. *Water SA* 34, 323–330.
- Kourgialas, N.N., Karatzas, G.P., 2011. Flood management and a GIS modelling method to assess flood-hazard areas—a case study. *Hydrol. Sci. J.* 56, 212–225.
- Kovács, Z., 1988. Regional Maximum Flood Peaks in Southern Africa. Report no. TR137, Department of Water Affairs and Forestry, Pretoria.
- Kundzewicz, Z.W., Kanae, S., Seneviratne, S.I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L.M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G.R., Kron, W., Benito, G., Honda, Y., Takahashi, K., Sherstyukov, B., 2013. Flood risk and climate change: global and regional perspectives. *Hydrol. Sci. J.* 59, 1–28.
- Lane, S.N., Brookes, C.J., Hardy, R.J., Holden, J., James, T.D., Kirkby, M.J., McDonald, A.T., Tayefi, V., Yu, D., 2003. Land management, flooding and environmental risk: New approaches to a very old question. In: *Proceedings of the CIWEM National Conference. National Conference of the Chartered Institution of Water and Environmental Management (CIWEM), Harrogate, September 2003.*
- Lane, S.N., Reaney, S.M., Heathwaite, A.L., 2009. Representation of landscape hydrological connectivity using a topographically driven surface flow index. *Water Resour. Res.* 45, 0–10.
- Longobardi, A., Villani, P., Grayson, R.B., Western, A.W., 2003. On The Relationship Between Runoff Coefficient And Catchment Initial Conditions. In: *Proceedings of the International Congress on Modelling and Simulation, Vol. 2. Modell. and Simul. Soc. of Australia and New Zealand, Townsville, Australia., pp. 867–872.*
- Lund, B.G.A., 1984. The Mfolozi flood of 31 January 1984. *Civ. Eng.* 26, 116–117.
- Manfreda, S., Scanlon, T.M., Caylor, K.K., 2010. On the importance of accurate depiction of infiltration processes on modelled soil moisture and vegetation water stress. *Ecohydrology* 3, 155–165.
- McDonnell, J.J., 2009. Hewlett, J.D. and Hibbert, A.R. 1967: Factors affecting the response of small watersheds to precipitation in humid areas. In *Sopper, W.E. and Lull, H.W.,*



- editors, *Forest hydrology*, New York: Pergamon Press, 275--90. *Prog. Phys. Geogr.* 33, 288–293.
- McLaughlin, D.L., Cohen, M.J., 2013. Realizing ecosystem services: wetland hydrologic function along a gradient of ecosystem condition. *Ecol. Appl.* 23, 1619–31.
- Melenti, L.I., Keri, A.A., Rusu, T., 2011. Soil Conservation Service Curve Number Method for Surface Runoff Estimation Using GIS Techniques, in Roşia Poieni Mining Area (Romania). *ProEnvironment* 4, 240–246.
- Merz, R., Blöschl, G., 2008a. Flood frequency hydrology: 1. Temporal, spatial, and causal expansion of information. *Water Resour. Res.* 44, n/a-n/a.
- Merz, R., Blöschl, G., 2008b. Flood frequency hydrology: 2. Combining data evidence. *Water Resour. Res.* 44, n/a-n/a.
- Milly, P.C.D., Wetherald, R.T., Dunne, K.A., Delworth, T.L., 2002. Increasing risk of great floods in a changing climate. *Nature* 415, 514–7.
- Mkhandi, S.H., Kachroo, R.K., Gunasekara, T.A.G., 2000. Flood frequency analysis of southern Africa : II . Identification of regional distributions. *Hydrol. Sci. J.* 45, 449–464.
- Mukheibir, P., Ziervogel, G., 2007. Developing a Municipal Adaptation Plan (MAP) for climate change: the city of Cape Town. *Environ. Urban.* 19, 143–158.
- Musungu, K., Motala, S., Smit, J., 2012. Using Multi-criteria Evaluation and GIS for Flood Risk Analysis in Informal Settlements of Cape Town: The Case of Graveyard Pond. *South African J. Geomatics*.
- Nortje, J.H., 2010. Estimation of extreme flood peaks by selective statistical analyses of relevant flood peak data within similar hydrological regions. *J. South African Inst. Civ. Eng.* 52, 48–57.
- Olaya, V., 2004. A gentle introduction to SAGA GIS.
- Pegram, G., Parak, M., 2004. A review of the regional maximum flood and rational formula using geomorphological information and observed floods. *Water SA* 30, 377–392.
- Pharoah, R., Holloway, A., Fortune, G., Chapman, A., Schaber, E., Zweig, P., 2016. OFF the RADAR: Synthesis Report. High Impact Weather Events in the Western Cape, South Africa 2003 – 2014 52.



- Prudhomme, C., Wilby, R.L., Crooks, S., Kay, A.L., Reynard, N.S., 2010. Scenario-neutral approach to climate change impact studies: Application to flood risk. *J. Hydrol.* 390, 198–209.
- Pyle, D.M., Jacobs, T.L., 2016. The Port Alfred floods of 17-23 October 2012: A case of disaster (mis)management? *Jàmbá J. Disaster Risk Stud.* 8, 8 pages.
- Roberts, C.P.R., Alexander, W.J.R., 1982. Lessons learnt from the 1981 Laingsburg Flood. *Civ. Eng. South Africa* 24, 17–27.
- Rufat, S., Tate, E., Burton, C.G., Maroof, A.S., 2015. Social vulnerability to floods: Review of case studies and implications for measurement. *Int. J. Disaster Risk Reduct.* 14, 470–486.
- Sakulski, D., 2007. Spatial and temporal frequency and distribution of hazardous events over South African territory for the period between years 1800 and 1995 based on 'CAELUM' document, Pretoria. Cooperation Unit for Southern Africa, United Nations University, Nairobi.
- SANBI, 2014. A Framework for investing in ecological infrastructure in South Africa. South African National Biodiversity Institute, Pretoria.
- SANBI, 2015. Washed away. Ecological infrastructure, Case study 4, South African National Biodiversity Institute, Pretoria.
- Sayama, T., McDonnell, J.J., Dhakal, A., Sullivan, K., 2011. How much water can a watershed store? *Hydrol. Process.* 25, 3899–3908.
- Schulze, R.E., Maharaj, M., Warburton, M.L., Gers, C.J., Horan, M.J.C., Kunz, R.P., Clark, D.J., 2008. South African Atlas of Climatology and Agrohydrology. Report No. 1489/1/08, Water Research Commission, Pretoria. Pretoria.
- Smithers, J., 2012. Methods for design flood estimation in South Africa. *Water SA* 38, 687–703.
- Smithers, J., Streatfield, J., Gray, R., Oakes, E., 2015. Performance of regional flood frequency analysis methods in KwaZulu-Natal, South Africa. *Water SA* 41, 390.
- Smithers, J.C., Chetty, K.T., Frezghi, M.S., Knoesen, D.M., Tewolde, M.H., 2013. Development and assessment of a daily time-step continuous simulation modelling approach for design flood estimation at ungauged locations: ACRU model and Thukela Catchment case study. *Water SA* 39, 467–476.



- Smithers, J.C., Schulze, R.E., 2003. Design rainfall and flood estimation in South Africa. Report on Project No K5/1060, Water Research Commission, Pretoria, Pietermaritzburg.
- Smithers, J.C., Schulze, R.E., 2004. The estimation of design rainfalls for South Africa using a regional scale invariant approach. *Water SA* 30, 435–444.
- Smithers, J.C., Schulze, R.E., Pike, A., Jewitt, G.P.W., 2001. A hydrology perspective of the February 2000 floods: A case study in the Sabie River Catchment. *Water SA* 27, 325–332.
- Steinschneider, S., Wi, S., Brown, C., 2015. The integrated effects of climate and hydrologic uncertainty on future flood risk assessments. *Hydrol. Process.* 29, 2823–2839.
- Thomas, A., 2015. Modelling of Spatially Distributed Surface Runoff and Infiltration in the Olifants River Catchment / Water Management Area Using GIS. *Int. J. Adv. Remote Sens. GIS* 4, 828–862.
- Thorslund, J., Jarsjo, J., Jaramillo, F., Jawitz, J.W., Manzoni, S., Basu, N.B., Chalov, S.R., Cohen, M.J., Creed, I.F., Goldenberg, R., Hylin, A., Kalantari, Z., Koussis, A.D., Lyon, S.W., Mazi, K., Mard, J., Persson, K., Pietro, J., Prieto, C., Quin, A., Van Meter, K., Destouni, G., 2017. Wetlands as large-scale nature-based solutions: Status and challenges for research, engineering and management. *Ecol. Eng.* 108, 489–497.
- Turner, B.L., Kasperson, R.E., Matson, P. a, McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Kasperson, J.X., Luers, A., Martello, M.L., Polsky, C., Pulsipher, A., Schiller, A., 2003. A framework for vulnerability analysis in sustainability science. *Proc. Natl. Acad. Sci. U. S. A.* 100, 8074–9.
- USDA, 1986. Urban Hydrology for Small Watersheds. United States Department of Agriculture, Natural Resources Conservation Service, Washington DC.
- Van Bladeren, D., Zawada, P.K., Mahlangu, D., 2007. Statistical Based Regional Flood Frequency Estimation Study for South Africa Using Systematic , Historical and Palaeoflood Data: Pilot Study – Catchment Management Area 15. Report No 1260/1/07, Water Research Commission, Pretoria.
- Van den Berg, E.C., Plarre, C., Van den Berg, H.M., Thompson, M.W., 2008. The South African National Land Cover 2000. No. GW/A/2008/86, Agricultural Research Council (ARC) and Council for Scientific and Industrial Research (CSIR), Pretoria.



- Van Niekerk, D., Murphree, M., Prinsloo, V., Lunga, W., Kruger, L., Bredenkamp, P.W., Nemakonde, L., Coetzee, C., 2016. Regional Assessment on Ecosystem-based Disaster Risk Reduction and Biodiversity in South Africa. Eastern and Southern Africa Regional Office, IUCN, Nairobi.
- Van Riet, G., van Niekerk, D., 2012. Capacity development for participatory disaster risk assessment. *Environ. Hazards* 11, 213–225.
- Viljoen, A., du Plessis, L.A., Booysens, H.J., Weepener, H.L., Braune, M., van Bladeren, D., Butler, M., 2001. Flood Damage Management Aids For Integrated Sustainable Development Planning in South Africa. Report No. 889/1/01, Water Research Commission, Pretoria.
- Viljoen, M.F., Booysen, H.J., 2006. Planning and management of flood damage control: the South African experience. *Irrig. Drain.* 55, S83–S91.
- Vischel, T., Pegram, G., Sinclair, S., Parak, M., 2008. Implementation of the TOPKAPI model in South Africa: Initial results from the Liebenbergsvlei catchment. *Water SA* 34, 331–342.
- Ward, P.J., Jongman, B., Weiland, F.S., Bouwman, A., van Beek, R., Bierkens, M.F.P., Ligtvoet, W., Winsemius, H.C., 2013. Assessing flood risk at the global scale: Model setup, results, and sensitivity. *Environ. Res. Lett.* 8, 44019.
- Winsemius, H.C., Aerts, J.C.J.H., van Beek, L.P.H., Bierkens, M.F.P., Bouwman, A., Jongman, B., Kwadijk, J.C.J., Ligtvoet, W., Lucas, P.L., van Vuuren, D.P., Ward, P.J., 2015. Global drivers of future river flood risk. *Nat. Clim. Chang.* 6, 381–385.
- Zerger, A., Wealands, S., 2004. Beyond Modelling: Linking Models with GIS for Flood Risk Management. *Nat. Hazards* 33, 191–208.
- Zhang, X., Wan, H., Zwiers, F.W., Hegerl, G.C., Min, S.-K., 2013. Attributing intensification of precipitation extremes to human influence. *Geophys. Res. Lett.* 40, 5252–5257.